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Joel Stoltzfus

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1.0 Introduction

Because most materials, including metals, burn in oxygen-enriched environments, hazards are always present when using oxygen. Most materials ignite at considerably lower temperatures in oxygen-enriched environments than in air, and, once ignited, combustion rates are greater in oxygen-enriched environments. Many metals burn violently in oxygen-enriched environments when ignited. Lubricants, tapes, gaskets, fuels, and solvents can increase the possibility of ignition in oxygen systems.

However, these hazards do not preclude the use of oxygen. Oxygen may be used safely if all the materials in a system are not flammable in the end-use environment or if ignition sources are identified and controlled. These ignition and combustion hazards necessitate a proper oxygen hazards analysis before introducing a material or component into oxygen service.

Further information on the safe design of oxygen systems can be found in the most current versions of ASTM G 63, ASTM G 88, and ASTM G 94; and NHB 8060.1C (1991), NFPA 50 (1990), NFPA 53M (1990), CGA G-4.0 (1987), CGA G-4.1 (1985), and CGA G-4.4 (1984).

The NASA Johnson Space Center White Sands Test Facility (WSTF) was requested by Cecil Hathaway of the U.S. Army Medical Research and Development Center, Ft. Detrich, Maryland, to perform a failure analysis on damaged hardware from a fire that occurred in a Field Medical Oxygen Generation and Distribution System (FMOGDS) Cylinder Filling Module (CFM) at the AMEDD C&S on August 12, 1994. After the failure analysis was performed, Mr. Hathaway requested that WSTF conduct a hazard analysis on the entire FMOGDS. The component assemblies to be analyzed are the Oxygen Generation Distribution Module (OGDM), the CFM, and the components connecting the two modules. This is a transportable system used to generate and distribute oxygen to both a field hospital and to individual storage cylinders for mobile use.

2.0 Objective

The objective was to perform an oxygen hazards analysis on the OGDM, the CFM, and the components connecting the two modules of the described system.

3.0 Approach

This hazard analysis was approached in two ways. First, the FMOGDS was evaluated at the system level according to ASTM G 88, Section 7, *Standard Guide for Designing Systems for Oxygen Service* (most current version). Second, the FMOGDS was evaluated at the component level as shown in Figure 1 and discussed at length in TP-WSTF-713 (Dees and Poe 1993). This approach is consistent with ASTM standards and guides for analyzing the hazards of components and systems exposed to oxygen-enriched environments.

The approach to this analysis is based on the premise that, usually, a fire will not occur in any environment unless the construction materials of the system or component are flammable <u>and</u> a credible ignition mechanism is present. The flammability of the material is first reviewed to determine if any fire hazards exist at the worst-case operating conditions. If the material is flammable, then the possible ignition mechanisms are surveyed to determine which are credible. If data for the particular ignition mechanism and the material(s) under consideration are not available, appropriate materials tests are conducted. Finally, the secondary and reaction effects are evaluated to determine what effect an ignition and possible combustion would have on the system and the facility.

To use this oxygen hazards analysis as a tool, individual analysis charts are recorded for each component or group of components. These charts contain the component designation, the flammability of component materials (metals and soft goods), the possible ignition mechanisms, the probability of each ignition mechanism, and the results of the secondary effects analysis and the reaction effects assessment. The documentation also includes any recommendations or limitations that the oxygen hazards team decides on, including recommendations of further testing if needed, stipulations of use, and any additional safety precautions. If component tests are required, these tests may be performed according to the *Guide for Oxygen Component Qualification Tests* (Bamford and Rucker 1992).

3.1 Material Flammability

The materials are evaluated to determine if they are flammable at the worst-case operating conditions. A large material flammability database at WSTF contains flammability data from previous and ongoing tests of both metals and polymers. If information on a material for the worst-case operating conditions cannot be located in the database, tests may be conducted to obtain this information. The oxygen hazards analysis chart is updated with the results, using *N* (nonflammable) or *F* (flammable). If the materials of a component are determined nonflammable, the ignition mechanisms need not be analyzed for that component.

3.2 Ignition Mechanisms

Next, an ignition mechanism survey is performed. Nine ignition mechanisms must be evaluated for each component found to have flammable materials.

- Frictional heating
- Adiabatic compression (pneumatic impact)
- Mechanical impact
- Particle impact
- Mechanical stress or vibration
- Static discharge
- Electric arc
- Chemical reaction
- Resonance

Each ignition mechanism must be evaluated to determine if it exists in the component and the likelihood that it will cause an ignition. The results of the analysis for each ignition mechanism are documented on the oxygen hazards analysis chart. Ratings for the ignition mechanisms are 0 (impossible), 1 (remote), 2 (unlikely), 3 (possible), and 4 (probable).

3.2.1 Frictional Heating

Parts of a component or system can rub against each other with enough force and/or velocity to raise any one part to its ignition temperature at the given oxygen pressure and concentration; for example, rotating or oscillating equipment and chattering relief valves.

3.2.2 Adiabatic Compression

A quantity of any gas can generate a considerable amount of heat if rapidly compressed. This heat can readily ignite polymers or flammable contaminants; for example, a downstream valve or flexible hose with a polymer liner in a dead-ended high-pressure oxygen manifold.

3.2.3 Mechanical Impact

An object with a relatively large mass or momentum striking a material can cause mechanical deformation and expose fresh surfaces; for example, a poppet of a solenoid-operated valve impacting the polymer seat.

3.2.4 Particle Impact

Combustible particles impinging on materials at velocities greater than 160 ft/s (50 m/s) in oxygen-enriched environments can cause ignition; for example, high-velocity particles from a dirty pipeline striking a valve plunger.

3.2.5 Mechanical Stress or Vibration

Materials that are poor heat conductors (such as plastics) can reach their ignition temperatures when stressed or vibrated; for example, unanchored joints that protrude inside piping.

3.2.6 Static Discharge

Discharges of static electricity can produce high temperatures, sometimes high enough to cause a material to reach its ignition temperature; for example, the accumulation of electrostatic charges created by the friction of dry oxygen flowing over nonmetals.

3.2.7 Electric Arc

Electric arcs can provide the energy to ignite materials in the presence of oxygen; for example, an insulated electrical heater short-circuiting and arcing through its sheath to the oxygen.

3.2.8 Chemical Reaction

An unrelated chemical reaction can produce sufficient heat to ignite materials in the presence of oxygen; for example, a chemical process that generates elevated temperatures.

3.2.9 Resonance

Acoustic oscillations within resonant cavities can cause a rapid gas temperature rise. The rise is more rapid and achieves higher values when particles are present. Ignition can result if the heat generated is not rapidly dissipated; for example, gas flow into a tee and out of a branch port so that the remaining closed port forms a resonant chamber.

3.2.10 Other Ignition Mechanisms

For each component, there may exist other ignition mechanisms besides those listed in the analysis chart. These ignition mechanisms are noted and evaluated accordingly.

3.2.11 Kindling Chain

If ignited, a component can cause a kindling chain reaction to ignite other components located nearby. This possibility is evaluated as an ignition hazard to nearby components and is noted as such.

3.3 Secondary Effects Analysis

After the ignition mechanisms have been surveyed, the secondary effects are analyzed. This analysis addresses the effects of failures that are not ignition related, but may create an ignition hazard in a nearby component, such as an external leak caused by normal seal wear. The leaking oxygen could build up and allow an ignition by the static discharge ignition mechanism in some nearby component. Ratings for the secondary effects analysis are + (further analysis of affected components necessary) and - (no further analysis needed).

3.4 Reaction Effects Assessment

Finally, a reaction effects assessment is performed and documented. This is an assessment of the effect if a component fails or is ignited and is useful for making judgments on the safe use of a component. The reaction effects assessment would then help determine if the component may be used safely. The ratings are *A* (negligible, no loss of equipment or life), *B* (marginal, equipment is damaged, but no lives are lost), *C* (critical, loss of test data and damage to equipment, but no loss of life), and *D* (catastrophic, loss of equipment and life).

4.0 System Description

The system analyzed consists of two modules, an OGDM (Figure 2) and a CFM (Figure 3). The OGDM feeds ambient air through a six stage compressor, then passes it through two adsorber vessels which adsorb nitrogen gas, leaving approximately 96 percent pure oxygen flowing at their outlets (the balance of which is Argon). The oxygen gas is further compressed, then distributed between the CFM and the field hospital. The CFM fills twelve D-size cylinders and one H-size cylinder with the product oxygen, then returns the high-pressure oxygen to the OGDM where it is stored in two high-pressure vessels. Only the individual components of both systems which are exposed to a high concentration of oxygen gas, and their connecting parts, are analyzed in detail in this document. Those components exposed only to air are not considered in this analysis.

4.1 Summary of Components

A list of FMOGDS components that were analyzed in this oxygen hazard analysis are shown in Table 1. The numbers given are FMOGDS numbers referenced in Figures 2 and 3. Numbers less than 100 can be referenced on the OGDM (Figure 2), and numbers greater than 100 can be referenced on the CFM (Figure 3).

Table 1
FMOGDS Components Analyzed

Component	Reference Numbers
Pressure Gauges	42, 45, 118
Pressure Transducers	16, 16A, 18A,B,C, 41, 114, 116, 136, 144A,B
Oxygen Compressor Assembly:	102-111
low/mid/high-pressure cylinders	
relief valve	
frame and running gear	
interstage coolers	
Manifold Valve Assembly:	124
3-way valve	
check valve	
passageways as sumps	
Cylinder Clamp Assembly	127
Oxygen Pressure Booster Pump Assembly:	32
low-pressure pump	
spacer between pump and motor	
Oxygen Filter, Metering Valve and Oxygen Analyzer Assembly	46 (119), 47 (120), 26-28 (121-123)
Relief Valves	22A, 31, 34, 36, 39, 112A, 116A
Check Valve	100, 113
High-Pressure Regulators	38, 115
Mass Flow Controllers	44, 44B
Manual Valves MV1-MV5	29A, 29, 117, 52C
Solenoid Valves	33, 100A, 115A, 133, 136A
High/Low-Pressure Flex Hoses & Quick Disconnects	(not shown in Figs. 2, 3)
Booster Inlet and Product Pressure Regulators	52AA, 35
Backup Oxygen Valve	37
Constant Purge Valve	25
Purge Control Valve & Manifold	24
Equalization Valve	23
Filters and Bleed Valves	101, 43
Vacuum Compressor	134
Oxygen Filter	132
Hardlines for OGDM & CFM	(not shown in Figs. 2, 3)
Temperature Indicators	112, 112B-F
Oxygen-Enriched Atmosphere (OEA) in Cabinet	(not shown in Figs. 2, 3)

5.0 Worst-case Operating Conditions

Each component is analyzed as if subjected to its worst-case (most severe) environment conditions. This information is used to evaluate the materials of construction for resistance to ignition and combustion and includes maximum use pressures and temperatures. In some cases, the maximum possible flow rate and velocity are also considered. The worst-case conditions for each component are described in their respective section. If the worst-case conditions are ambient, assume the maximum temperature is 120 °F (49 °C) and the maximum pressure is 14.7 psia (0.10 MPa) unless otherwise stated.

6.0 Results and Discussion

6.1 System Evaluation per ASTM G 88, Section 7

The following notes were taken on the FMOGDS overall system design, in accordance with guidelines found in ASTM G 88 Section 7, *Designing Systems for Oxygen Service*. The guide's reference numbers are identified for convenience.

7.3 Avoid Unnecessarily Elevated Temperatures

Elevated temperatures are possible in the following areas and are controlled as stated:

- A cooler exists in the OGDM cabinet with a 140 °F (60 °C) shutdown temperature.
- High temperature cut-offs exist on all six stages of the high-pressure oxygen compressor, with a maximum temperature of 300 °F (150 °C).
- Interstage cooling exists on the high-pressure oxygen compressor.
- Maximum temperature allowed on the six stages of the compressor are below the minimum Autogenous Ignition Temperature (AIT) for polymer materials (Table 2).
- Temperature is cooled by the end of the surge tank from the oxygen product booster pump.
- High-pressure compressor has interstage coolers with an aftercooler and an air blower on the front, driven by the shaft of the compressor, that provides cooling air for the compressor.
- High temperature zones are *limited* on both compressors.

7.4 Avoid Unnecessarily Elevated Pressures

Elevated pressures are possible in the following areas and are controlled as stated:

- A compressor exists in the CFM cabinet (pressurize near use point).

Table 2
Autogenous Ignition Temperatures and Oxygen Indexes (OI)

Material	AIT °F	AIT °C	OI
Nylon II (Nylon 6-6)	464	240[a]	24-30.1[b]
Vespel® SP-21	780	420[a]	65[b]
Polypropylene (pure)	410	210[c]	17.4[b]
Teflon® PTFE	800+	427+[d]	95[b]
Bronze-Filled[e]			
Glass-Filled[e]			
Kel-®F 81	800+	427+[d]	
Krytox® Grease	800+	427+[d]	
PVC	495	257[f]	37[b]
Buna-N®	912	489[g]	18[b]
Viton® A	514	268[h]	57[b]
Neoprene	321	161[h]	26.3[b]

[a]Swindells, I., et al., Spontaneous Ignition Temperatures of Nonmetals in Gaseous Oxygen, ASTM STP 986, 1988.
[b]ASTM G 63, "Guide for Evaluating Nonmetallic Materials for Oxygen Service." American Society for Testing and Materials, Philadelphia, PA, Appendix X1.5, 1987.
[c]Wharton, R.K., et al., "Further Studies of Factors that Affect the Spontaneous Ignition Temperatures of Non-Metallic Materials in Gaseous Oxygen," ASTM STP 1040, 1989.
[d]Lockhart, B.J., et al., "The Oxygen Sensitivity/Compatibility Ranking of Several Materials by Different Test Methods," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Fourth Volume*, ASTM STP 1040, Joel M. Stoltzfus, Frank J. Benz, and Jack Stradling, eds., American Society for Testing and Materials, Philadelphia, PA, 1989.
[e]Bronze and Glass Filled Teflon® not tested, but proposed to behave similarly to Teflon® PTFE.
[f]Wolf, G.L., et al., "Spontaneous Ignition Temperature of Tracheal Tubes," ASTM STP 1197, 1993.
[g]Shelley, R.M., et al., "Evaluation of Buna-N® Ignition Hazard in Gaseous Oxygen," ASTM STP 1197, 1993.
[h]ASTM G 63, "Guide for Evaluating Nonmetallic Materials for Oxygen Service." American Society for Testing and Materials, Philadelphia, PA, vol. 14.02, 1987.

- The nylon flex hose between the CFM and OGDM is at 2,250 psig (15.5 MPa) during the filling cycle for the backup supply cylinders (normal filling time is 5 hours with a 50-ft-long (15-m-long) hose).

- It was determined that this system is designed as well as possible on avoiding unnecessarily elevated pressures.

7.5 Design for System Cleanness

- Clean as per MIL STD 1330C, 5 ppm standard, for all in-house-cleaned parts.

- All other parts were purchased *Oxygen Clean*, from companies such as Tescom, Dresser Rand, Nupro, Whitey, Circle Seal, or Peter Paul. Also, engineering evaluations of each company's cleaning procedures has been done and visual inspection at the use point has been made. In addition, all lubricants have been specified and certified.

- It appears that *starting with clean parts* has been adequately addressed.

7.5.2 Avoid the presence of unnecessary sumps, dead-ends and cavities likely to accumulate debris

The FMOGDS system addresses this hazard as follows:

- The system solenoid valve assemblies are designed and implemented to avoid this problem. However, it is necessary to determine if the *passageways* in the system solenoid valve assembly are sump possibilities for particles.

- The oxygen inlets and outlets on the high-pressure oxygen storage bottles are located on top of the vertically oriented bottles.

- Operationally generated contaminant from compressors should be considered.

- Bottles being filled (H- and D-size cylinders) are sources of contaminant.

- Air intake is filtered by an inlet filter and coalescing filters (0.01 microns).

- Contamination potential exists with the connection or disconnection of the distribution hoses.

7.5.3 Filters to limit introduction of particles

- Air entry points are well filtered.

- Quick disconnects on distribution system hoses will be analyzed for this hazard.

- H- and D-size cylinder fill stations should consider filters at the bottle connection points, as close to the bottle connection point as practical.

- H-size cylinder filter should be analyzed for this hazard.

- Evaluate cylinder clamp assembly both with and without a filter.

- There are filters or *particle traps* near the outlets of both compressors.

- A product filter is located on the inlet to the CFM just downstream from the hose quick disconnect.

- All regulators, with the exception of high-pressure regulator 38, have line filters or particle traps upstream.

- Both high-pressure regulators 38 and 115 have filters.

7.6 Avoid Particle Impacts

7.6.2 Limit Gas Velocities to Limit Particle Kinetic Energies

- Velocity in product lines with 0.38-in. (0.95-cm) diameter is approximately 8.9 in/s (3.5 cm/s).

- Possible high velocity points include any valve going to vent, the compressor valves, and other pressure drops in the system.

7.6.5 Minimize Pressurization Rates

- A maximum of 200 psi (1.4 MPa) change in pressure exists on all SSV assemblies.

- A maximum rate of 200 psi/min (1.4 MPa/min) imposed on filling of storage cylinders. All cylinder filling is software controlled.

- No possibility exists of *transfilling* cylinders. The only filling mode is to use the compressor.

7.7 Avoid Heat of Compression

- No components are identified where heat of compression is a problem.

7.8 Avoid Friction and Galling

- This hazard pertains to compressors and will be analyzed accordingly.

7.9 Avoid Corrosion

- The entire system is enclosed in cabinets.

7.10 Avoid Resonance

- Not an issue in most system components.

7.11 Use Proven Hardware

- The only *unique* components in this system are the compressors and the manifold assembly.

7.12 Design to Manage Fires

- System is automated, avoiding *hands-on* use as much as possible.

- System is contained within cabinets.

7.13 Anticipate Indirect Oxygen Exposure

- If a leak should occur in the oxygen concentration monitor, the oxygen gas purity would not be maintained, thus the system shuts down and a backup system takes over.

- If a 100 psi (0.68 MPa) drop occurs in the backup system in one hour, then an alarm sounds, indicating that are leaks present.

- CFM compressor compartment doors are open during operation.

- Relay compartment is open to the compressor compartment. Consideration should be given to secondary oxygen exposure of the relay compartment components for both the OGDM and the CFM.

7.14 Minimize available fuel or oxygen

- Minimized as best as practical.

7.15.6 Provide the capability to start-up the system on inert gases as a means to seat surfaces, etc.

- Purging with GN_2 noted as a good practice, but conversion to oxygen should be made before distribution to patients' rooms.

6.2 Material Flammability of Soft Goods and Metals

6.2.1 Soft Goods and Lubricants

The OI of a material in an oxygen-enriched environment can be used as a guideline to determine the relative flammability of component soft goods and lubricants. The OI is the minimum concentration of oxygen, expressed as volume percent, in an ascending flow of oxygen and nitrogen, at one atmosphere pressure, that will just sustain equilibrium combustion of a top-ignited, vertical test specimen (ASTM D2863).

The AIT of a material in an oxygen-enriched environment is the temperature at which a material can be spontaneously ignited at various pressures (ASTM G 72). The AIT's of the soft goods and lubricant materials in this analysis, along with their OI's, were previously shown in Table 2.

6.2.2 Metals

The threshold pressure of a metal is defined as the minimum oxygen pressure required to support upward self-sustained combustion of a 3.2-mm-diameter (0.125-in.-diameter) rod ignited at the bottom. The threshold pressure can be used as a guideline to determine the relative flammability of the metal materials in a component. Table 3 contains the threshold pressures of the metals found in this analysis.

Table 3
Threshold Pressures

Material	Threshold Pressure (psi)	Threshold Pressure (MPa)
Stainless Steel		
303	1,000	6.9[a]
304	1,000 gage	7.0[b]
316	1,000 gage	7.0[c]
321	1,000	6.9[a]
440A	3,000	20.7[a]
440C	2,500	17.2[a]
17-4 PH	1,000	6.9[a]
Carbon Steel		
	100 gage	0.77[d]
	29 gage	0.29[e]
Brass		
360 CDA	>10,000	68.9[a]
Red/Yellow	>7,000	48.3[a]
Aluminum		
99.9% Pure	25	0.17[a]
6061-T6	100	0.7[a]
5058	35	0.2[a]
Copper		
Cu-Cr	>10,000	68.9[a]
102	>8,000 gage	>55[a]

[a]Unpublished data from WSTF Promoted Combustion Tests.
[b]Bryan, C.J., Stoltzfus, J.M., and Gunaji, M.V. "An Assessment of the Metals Flammability Hazard in the Kennedy Space Center Oxygen Systems," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Fifth Volume, ASTM STP 1111*, Joel M. Stoltzfus and Kenneth McIlroy, eds., American Society for Testing and Materials, Philadelphia, PA, 1991.
[c]Benz, F.J., Shaw, R.C., and Homa, J.M. "Burn Propagation Rates of Metals and Alloys in Gaseous Oxygen," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Second Volume, ASTM STP 910*, M.A. Benning, ed., American Society for Testing and Materials, Philadelphia, PA, 1986.
[d]McIlroy, K. and Zawierucha, R. "The Effects of Testing Methodology on the Promoted Ignition-Combustion Behavior of Carbon Steel and 316L Stainless Steel in Oxygen Gas Mixtures," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Fourth Volume, ASTM STP 1040*, Joel M. Stoltzfus, Frank J. Benz, and Jack S. Stradling, eds., American Society for Testing and Materials, Philadelphia, PA, 1989, pp. 38-53.
[e]Sato, J. "Fire Spread Rates Along Cylindrical Metal Rods in High Pressure Oxygen," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Fourth Volume, ASTM STP 1040*, Joel M. Stoltzfus, Frank J. Benz, and Jack S. Stradling, eds., American Society for Testing and Materials, Philadelphia, PA, 1989.

6.3 Evaluation of Components

The following legend applies to all component analysis summary charts:

Legends:

Material Flammability	Ignition Hazards	Secondary Effect	Reaction Effect
F = Flammable	0 = Almost impossible	+ = Analysis of Affected Components Needed	A = Negligible
N = Nonflammable	1 = Remotely possible	- = No Further Analysis Needed	B = Marginal
	2 = Possible		C = Critical
	3 = Probable		D = Catastrophic
	4 = Highly Probable		

6.3.1 Pressure Gages 42, 45, 118

The schematic of pressure gages 42, 45, and 118 is shown in Figure 4. Both the Bourdon tube and socket are made of 316 stainless steel (SS) and the pipe threads are wrapped with Teflon® tape. The worst-case operating temperature and pressure for these gages are 120 °F (49 °C) and 2,250 psig (15.5 MPa), respectively.

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Pressure Gauges	F	F	0	1	0	0	0	0	0	0	0	0	0	-	C

Note: The data are for pressure gauge #'s 42, 45, and 118.

NOTES: Adiabatic compression is a remotely possible ignition hazard. The worst-case scenario is when a vented line is rapidly pressurized to a gage. For example, opening Manual Valve 1 (29A) or 2 (29A) may rapidly pressurize gage 42. Also, only gage 45 has a Snubber fitting to protect it from pressure surges and shocks. However, adiabatic compression is only a remotely possible ignition source because MV1 and 2 are slow-opening valves and, thus, guard against rapid pressurization. The Teflon® tape on these pressure gages should be installed with good practice; that is, no tape should cover the last two threads. If these gages are contaminated with hydrocarbon oil upon installation or cleaned with a flammable cleaning solvent, then the ignition hazard by pneumatic impact increases to possible, or even probable. Ensure that procurement, assembly, and operational documentation include warnings that oxygen assembly or disassembly must be done properly, cleanliness must be maintained, only clean components, parts, and tools must be used, and flammable solvents must not be used to clean parts.

6.3.2 Pressure Transducers 16, 16A, 18A, 18B, 18C, 41, 114, 116, 136, 144A, 144B

These pressure transducers are diaphragm-type transducers with a 300-series SS diaphragm, housing, and fitting. The worst-case operating temperature and pressure is 120 °F (49 °C) and 2,250 psig (15.5 MPa), respectively.

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Pressure Transducers	F	F	0	1	0	0	0	0	0	0	0	0	0	-	B

Note: The data are for pressure transducer #'s 16, 16A, 18A,B,C; 41, 114, 116, 136, and 144A,B.

NOTES: Adiabatic compression is a remotely possible ignition source in these transducers. As with the pressure gages, the worst-case scenario is when a vented line is rapidly pressurized to a transducer. See notes under pressure gages above for safety precautions against adiabatic compression.

The reaction effects assessment is marginal. If pressure transducers did burn, other components would be lost.

6.3.3 Oxygen Compressor Assembly 102-111

Oxygen Compressor Assembly	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Low Pressure Cylinder	N	F	2	0	0	0	0	0	0	0	0	0	0	-	C
Mid Pressure Cylinder	N	F	2	0	0	0	0	0	0	0	0	0	0	-	C
High Pressure Cylinder	F	F	3	0	0	0	0	0	0	0	0	0	0	-	B
Relief Valve	F	F	1	0	0	1	0	0	0	0	0	0	0	-	B
Frame and Running Gear	N/F	F	1	0	0	0	0	0	0	0	0	0	0	-	B
Interstage Coolers	N	-	0	0	0	0	0	0	0	0	0	0	0	-	B

Note: Refer to Item #'s 102 through 111.

6.3.3.1 Low-Pressure Cylinder

The schematic of the low-pressure cylinder is shown in Figure 5a. The body is 300- and 400-series SS with Viton® and Teflon® O-rings. The washer is made of Vespel® SP-21 and the reed valve is made of 17-4 PH SS. The worst-case operating temperature and pressure is 300 °F (150 °C) and 300 psig (2 MPa) at the upper head.

NOTES: Frictional heating is a possible ignition hazard around the stainless steel piston. However, at this point, the pressure and temperatures are normally low. In the discharge head, the Teflon® O-rings rub against stainless steel at a high pressure, which could cause high temperatures, but a low coefficient of friction between Teflon® and stainless steel prevents this. In the cylinder there are low normal loads and good mechanical stability of the piston, both reducing frictional heating.

Adiabatic compression is an almost impossible ignition source because of the low pressure rates in this cylinder.

Particle impact is also an almost impossible ignition source as only low gas velocities exist through the reed valve.

Mechanical stress or vibration also has a hazard rating of zero, as no yielding occurs in the reed valve.

There are no hazardous secondary effects. If three pressure seals fail, no pressure will build in the cylinder. This is a detectable failure and not a problem because the guide ring is still holding the piston. If all seals fail and the guide fails, friction between the stainless steel piston and the stainless steel cylinder occurs, but the temperature is below the flammability threshold of stainless steel.

The reaction effects assessment is critical on the low-pressure cylinder. If a fire occurred people might get hurt; it is a manned operation.

6.3.3.2 Mid-Pressure Cylinder

The schematic of the mid-pressure cylinder is shown in Figure 5b. Like the low-pressure cylinder, the body is 300- and 400-series SS with a 300-series SS piston and a 420 SS cylinder. Inside the cylinder are bronze-filled Teflon® seals and a Vespel® SP-21 follower. Worst-case operating conditions include a maximum temperature of 300 °F (150 °C) at the upper head and a maximum pressure of 1,100 psig (7.6 MPa) in the head chamber, with a discharge pressure of 2,250 psig (15.5 MPa).

NOTES: Frictional heating is a possible ignition hazard in the mid-pressure cylinder as heat may be generated along the sidewall from the stroke of the piston. As in the low-pressure cylinder, polymers rub against stainless steel throughout the stroke, but the coefficient of friction is too low for ignition to occur. In addition, stainless steel is not flammable in this setting due to its large bulk (the thickness is greater than 2.5 in. (0.64 cm). In the event of some polymer failure, metal rubbing on metal could cause galling between the 420 SS (hardened) cylinder and the 300-series (nonhardened) piston parts. The piston parts, being the softer material, will gall if friction occurs, possibly producing enough heat for ignition. Therefore, the flammability is controlled by the softer piston parts.

Adiabatic compression is an almost impossible ignition hazard. Rapidly compressing the oxygen gas inside the cylinder creates a pressure ratio of two to one, generating a maximum temperature which is much less than the AIT (ASTM G 63).

Particle impact is also an almost impossible source of ignition as the gas velocities are too low to create an impact hazard.

The reaction effects assessment is critical for the same reason as in the low-pressure cylinder. It is a manned operation, and if a fire occurred, human lives would be in danger.

6.3.3.3 High-Pressure Cylinder

The schematic of the high-pressure cylinder is shown in Figure 5c. Like the mid-pressure cylinder, the body is 300- and 400-series SS with a 300-series SS piston and a 420 SS cylinder. The polymers are also Teflon® and Viton® with a Vespel® SP-21 follower. The worst-case operating temperature and pressure are 300 °F (150 °C) and 1,100 psig (7.6 MPa) in the head chamber, with a 2,250 psig (15.5 MPa) discharge pressure.

NOTES: Frictional heating is a probable source of ignition in the high-pressure cylinder. Heat from friction can be generated by the same sources as in the low- and mid-pressure cylinders. However, in the high-pressure cylinder, if metal rubs metal from a polymer failure or a bent piston shaft, and loads of approximately 80 lbf (360 N) can be generated normal to the cylinder wall, then a probable ignition hazard exists (rating = 3). If the piston shaft were bent and rubbed through the Vespel® SP-21 guide ring, a normal load of approximately 80 lbf (360 N) would result, assuming the seals were still holding pressure, the compressor motor was still functioning, and at least one quarter of the circumference of the piston shaft is in contact with the cylinder. To lower the hazard rating to a possible rating of two or less, proof must be given that such a normal force could not occur and/or proper assembly procedures would not allow a bent shaft to be admitted.

Adiabatic compression is an almost impossible ignition hazard. As found in the mid-pressure cylinder, rapidly compressing the oxygen gas inside the cylinder creates a pressure ratio of 2 to 1, generating a maximum temperature which is much lower than the AIT (ASTM G 63).

The particle impact ignition hazard is, again, almost impossible because the gas velocities are too low.

The reaction effects assessment is only marginal in the high-pressure cylinder. Previous fires have been observed in compressor equipment with large wall thicknesses, like this cylinder, and the fire did not burn through the cylinder wall. Personnel standing by would be protected from a fire, and thus, a marginal rating of two is given.

6.3.3.4 Compressor Relief Valve

The relief valve has a 300-series SS body, spring, and plunger, with a Teflon® seat and Viton® O-rings. The worst-case operating conditions include a maximum temperature of 150 °F (66 °C) and a maximum pressure of 1,100 psig (7.6 MPa).

NOTES: Frictional heating is a remotely possible ignition source in the relief valve. Normal forces are low, and galling is unlikely. Therefore, the probability of ignition is low.

Adiabatic compression is an almost impossible ignition hazard. The oxygen gas rapidly compresses from 500 psig (3.4 MPa) to 1000 psig (6.9 MPa) at the valve, a pressure ratio of two. Therefore, theoretically, Teflon® and other polymers won't ignite by adiabatic compression. (The maximum theoretical temperature obtained when rapidly compressing oxygen from 500 psig (3.4 MPa) to 1000 psig (6.9 MPa) is less than the AIT of these polymers (ASTM G 63)).

An ignition in the relief valve caused by mechanical impact is considered almost impossible. The most severe impact in the valve occurs when the poppet drops against its seat from a completely open position. This scenario creates an impact energy of 12.5 in-lb (0.14 kgf-m) (manufacturer specifications), dramatically less than the 72 ft-lb (10 kgf-m) used for impact ignition of Teflon®. High-pressure gaseous oxygen mechanical impact test results show four ignitions in 20 tests at ambient temperature, at a 34 MPa (4,930 psia) pressure, and at a 10 kgf-m (72 ft-lbf) impact energy on a 1.57-mm (0.062-in.) thick sample (Bryan 1991).

Particle impact is a remotely possible ignition hazard in the relief valve. High gas velocities exist, and particles may be present. However, stainless steel has not ignited in particle impact tests (PIT) using Teflon® particles, only using aluminum (Al) particles.[1] Bronze-filled Teflon® is proposed to behave like Teflon® with respect to particle impact.

Secondary effects analysis concludes that no further analysis is needed. If the relief valve fails closed, then pressure is not relieved. But, high temperatures created by high pressures are monitored. Temperatures greater than 275 °F (135 °C) automatically turn off the compressor.

The reaction effects assessment on the relief valve is marginal. If the component burns, other components might be destroyed but human life is not in danger.

6.3.3.5 Frame and Running Gear

The schematic of the frame and running gear of the oxygen compressor assembly is shown in Figure 5d. The body of the frame is stainless steel with bronze-filled Teflon® seals, Timken 52100 carbon steel rolling element bearings, and Krytox® 240 AC lubricant throughout. The worst-case operating temperature is ambient temperature. The worst-case operating pressure is 25 psig (0.17 MPa) with the failure of a piston seal. Otherwise, 2.0 psig (0.01 MPa) is the normal operating pressure.

NOTES: The metals in this component are nonflammable under normal conditions because the gas pressure is low. However, the metals are considered flammable if a single failure occurs as the oxygen pressure in the frame housing would increase significantly.

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[1] Unpublished WSTF Particle Impact Test Data. NASA White Sands Test Facility, Las Cruces, NM.

Frictional heating is only a remotely possible ignition hazard in the frame and running gear. Two failures are required for a frictional heating ignition hazard to exist. If the roller bearings failed, then another failure must exist, which would increase the oxygen pressure enough to make the metals flammable.

6.3.3.6 Interstage Coolers

The interstage coolers are made of stainless steel tubing. They have worst-case operating conditions of ambient temperature and pressure except at the high-pressure cylinder, where the pressure can reach 2,250 psig (15.5 MPa).

NOTES: The tubing is considered flammable only at the high pressure. In all other situations, the stainless steel is nonflammable. There are no soft goods in this component.

Particle impact ignition hazards are almost impossible in the interstage coolers as the gas velocities are very low.

6.3.4 Manifold Valve Assembly 124

Manifold Valve Assembly	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
3-Way Valve	N/F	F	0	0	0	3	0	0	0	0	0	3	3	-	B
Check Valve	F	F	0	0	0	0	0	0	0	0	0	0	0	-	B
Passageways	N	-	0	0	0	0	0	0	0	0	0	0	0	+	B

Note: Refer to Item #124.

6.3.4.1 3-Way Solenoid Valve

The schematic of manifold valve assembly 124 is shown in Figure 6. The 3-way solenoid valve has a brass housing and manifold body with a 316 SS poppet and Vespel® SP-21 seat. The polymers include Vespel® SP-21 seats, Viton® stem seals, and a Teflon® backup ring. The worst-case operating temperature and pressure are 120 °F (49 °C) and 2,250 psig (15.5 MPa), respectively. The biggest change in pressure is from 2,250 psig (15.5 MPa) to ambient inside the D-size cylinder.

NOTES: The metal materials of the valve body are nonflammable, but the internal metals are considered flammable at the high pressure if ignited.

Adiabatic compression is an almost impossible ignition hazard in the 3-way solenoid valve as there is no operational mechanism to get rapid compression on the valve. During the fill cycle, the valve pressure is balanced by computer control.

Mechanical impact is also considered an almost impossible ignition hazard. High-pressure gaseous oxygen mechanical impact test results indicate that a 15.2 ft-lbf (2.1 kgf-m) is required to ignite Vespel® SP-21 by mechanical impact. In three out of 20 tests, ignition occurred when testing a 1.57-mm (0.062-in.) sample at 34.0 MPa (4930 psia). These high ignition energies can not be generated in this valve. Mechanical impact ignition could be augmented by the presence of large, hard contaminant particulate acting as a load concentrating grit. If the valve is kept clean, however, mechanical impact is not an issue.

Particle impact in the 3-way solenoid valve is a probable ignition hazard. High velocities will occur when venting to ambient pressure. In this case, the polymer (Vespel® SP-21) seat is vulnerable as an ignition source, not the metal. If contaminant is kept out of valve, this rating could be decreased. It is recommended that a filter be placed upstream of the 3-way solenoid valve, near the cylinder clamp assembly. This could reduce the given ignition hazard to a possible rating of two. Implementation of a filter is planned.

Other ignition mechanisms can also be probable ignition hazards, such as the combination of mechanical impact and contaminant. Again, if contaminant is kept out of the valve, this rating is decreased. A filter is planned to be installed upstream of the 3-way solenoid valve.

Kindling chain is a probable ignition source in the 3-way solenoid valve. With the current manifold valve assembly, a kindling chain hazard exists between the Vespel® SP-21 and 300-series SS. If the stainless steel is replaced by a nonflammable metal, then the kindling chain ignition hazard is reduced.

The reaction effects of a failure or fire in this component is marginal. The valve body is brass and nonflammable, thus human life is not threatened.

6.3.4.2 Check Valve

Figure 6 shows the check valve as part of the manifold valve assembly. The body is brass, the poppet is 316 SS, and the valve seat is Viton®. The valve also has a Viton® O-ring seal. Worst-case operating conditions include ambient temperature and a pressure of 2,250 psig (15.5 MPa). Also, the largest change in pressure is maximum pressure to ambient.

NOTES: Adiabatic compression is an almost impossible ignition hazard. No operational mechanism exists to get rapid compression on the valve. During the fill cycle, pressure is balanced to less than 200 psi (1.4 MPa) by computer control.

Particle impact is also an almost impossible ignition hazard because the oxygen gas velocity is too low to ignite any particles that might enter the system.

As with the 3-way valve, the reaction effects assessment is only marginal because of the nonflammable brass housing and body.

6.3.4.3 Passageways

The passageways of the manifold valve assembly, Figure 6, are analyzed as sumps for particles to collect. The passageways are inside the brass body. The worst-case operating temperature and pressure are 120 °F (49 °C) and 2,250 psig (15.5 MPa), respectively.

NOTES: The brass body is nonflammable under these conditions. There are no soft goods in this component.

The secondary effects analysis shows that the 3-way solenoid valve will, of course, be affected if a failure occurred in the passageways. A particle trapped in the passageway could cause an ignition hazard in the 3-way valve.

Again, the brass body of the manifold valve assembly is nonflammable. This makes the reaction effects marginal.

6.3.5 Cylinder Clamp Assembly 127

The schematic of the cylinder clamp assembly is shown in Figure 7. The body of the clamp assembly is brass. The oxygen-wetted parts include a brass thread insert, a 304 CRES A fitting, and a Viton® O-ring at the port. Two 410 or 416 guide pins are nonwetted, along with a nylon bushing. The worst-case operating temperature is 120 °F (49 °C), and the worst-case operating pressure is 2,250 psig (15.5 MPa).

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Cylinder Clamp Assembly	N	F	0	0	0	0	0	0	0	0	0	0	0	-	B

Note: Refer to Item #127.

NOTES: Frictional heating is an almost impossible ignition hazard in the clamp assembly. No frictional heat is created when mounting the cylinder or when it is in use.

Adiabatic compression is also an almost impossible source of ignition. No dead ends exist when the cylinder is mounted.

Mechanical impact is not an ignition hazard in this component as there is no movement of parts or springs when the cylinder is mounted.

6.3.6 Oxygen Pressure Booster Pump Assembly 32

6.3.6.1 Low-Pressure Booster Pump

The schematic of the low-pressure booster pump is shown in Figure 8. The booster pump has a bronze casing, a 300-series SS piston, a 420 SS cylinder, a 17-4 PH steel reed valve, bronze-filled Teflon® seal rings, and a glass-filled Teflon® shaft seal. Worst-case operating conditions include a temperature of 300 °F (150 °C) and a pressure of 70 psig (0.48 MPa).

Oxygen Pressure Booster Pump Assembly	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Low Pressure Booster Pump	N	F	2	0	0	0	0	0	0	0	0	0	0	+	B
Spacer Between Pump & Motor	N	F					1								

Note: Refer to item #32.

NOTES: Frictional heating is considered a possible ignition hazard in the low-pressure pump. The polymers have a low coefficient of friction and the metals are not flammable. However, some side loads are present.

Particle impact is an almost impossible source of ignition as the gas velocities in the pump are too low to ignite particles.

Failure of the low-pressure pump would have a definite affect on the spacer between the pump and motor, potentially creating an ignition hazard. This drive housing spacer has an aluminum shell and a nylon flex coupling, making it flammable in an oxygen-enriched environment. It is, however, contained by an aluminum spacer. Thus, the secondary effects on this component need analysis.

The reaction effects from this component are marginal. If a fire occurs, equipment may be damaged, but the cabinet is closed to protect personnel.

6.3.6.2 Spacer Between Pump and Motor

The spacer between the pump and the motor is aluminum. A nylon flex coupling also exists. The worst-case operating conditions are the same as the low-pressure booster pump, 300 °F (150 °C) and 70 psig (0.48 MPa).

NOTES: Only the mechanical stress of the spacer is analyzed. The ignition hazard is remotely possible as the nylon coupling contained by the aluminum spacer is a poor heat conductor and might reach its ignition temperature when stressed by the booster pump.

6.3.7 Oxygen Filter, Metering Valve, Oxygen Analyzer Assemblies

6.3.7.1 Oxygen Filters 46, 119

The schematic of the oxygen filters is shown in Figure 9. The filters have a 316 SS body, gasket, and filter element, and a 302 SS spring. The worst-case operating conditions are ambient temperature and a pressure of 70 psig (0.48 MPa).

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Oxygen Filter	N/F	-	0	0	0	0	0	0	0	0	0	0	0	-	A
Metering Valve	N	F	0	0	0	0	0	0	0	0	0	0	0	-	A
Oxygen Analyzer	N	F	0	0	0	0	0	0	0	0	0	0	0	+	A

Note: Refer to item #'s 46 and 119 for the oxygen filter, item #'s 47 and 120 for the metering valve, and item #'s 26 through 28 and 121 through 123 for the oxygen analyzer.

NOTES: The metals that comprise the body of the filter are nonflammable. However the element inside the filter is flammable. There are no soft goods in these filters.

If the filter fails or ignites, the reaction effects are negligible. Backup equipment is available and no human lives are threatened.

6.3.7.2 Metering Valves 47, 120

The schematic of these metering valves is shown in Figure 10. The valve body material is 316 SS. The handle, nut, and bonnet are also 316 SS. The 17-4 PH stem has Viton® O-ring seals and Krytox® 240 AC lubricants. The worst-case operating conditions are ambient temperature and a pressure of 70 psig (0.48 MPa).

NOTES: Particle impact is an almost impossible ignition hazard in the metering valve. The valve metals are not flammable and a filter is located just upstream.

6.3.7.3 O2 Analyzer 26-28, 121-123

The schematic of the oxygen analyzer is shown in Figure 11. The inlet tube is made of copper with a Viton® O-ring. The rest of the tubing is Viton®, connected by a polypropylene *tee*. The housing is Al 6061-T6. Worst-case operating conditions include ambient temperature and a pressure just over ambient to account for flow losses through the tubing. The flow rate of oxygen gas is 3.7 in^3/min (60 cm^3/min).

NOTES: The secondary effects analysis shows that a potential leak of oxygen gas into the housing needs to be further analyzed.

If the housing becomes enriched with oxygen, electrical components could be at risk. The housing metals are nonflammable, but the housing soft goods are flammable in an oxygen-enriched environment. Electrical arc is considered an almost impossible ignition hazard because the thermostat is hermetically sealed, precluding oxygen from getting to the contacts.

6.3.8 Relief Valves

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Relief Valves #39 and 112A	F	F	2	0	2	2	0	0	0	0	0	0	0	-	B

6.3.8.1 Relief Valves 39, 112A

The schematic of relief valves 39 and 112A is shown in Figure 12. The housing, poppet nut, spring guide, and shim of the valve are all 303 SS. The spring is 17-7 PH SS and all O-rings are Viton®. The worst-case operating temperature and pressure are 120 °F (49 °C) and 2,250 psig (15.5 MPa), respectively.

NOTES: Frictional heating is considered a possible ignition hazard. Frictional heating is only an issue if the valve chatters, possibly generating heat along the side wall of the valve. Because of its design, however, the valve has low side loads, minimizing frictional heat build-up along the side wall. Also, operational controls in the system are intended to avoid high pressures and cracking the valve.

Mechanical impact is also a possible ignition hazard if the valve chatters. The quick, continuous impact between metal and polymer as the valve reseats can possibly create enough heat to ignite the polymer. However, operational controls in the system are designed to avoid high pressures and cracking the valve.

Particle impact ignition in these relief valves is also a possible hazard. Ignition from this source is based on system cleanness. Particles potentially infiltrating the valve are polymers from the compressor, and stainless steel contaminant, generated during assembly. Stainless steel has been shown to ignite with aluminum particles (Particle impact test results show that 304L SS ignited in two out of two tests at 22 MPa (3,200 psig) and 544 K (520 °F) (Benz, Shaw, and Homa 1986)), but aluminum is excluded as possible contaminant in the system.

6.3.8.2 Relief Valves 34, 116A, 22A, 31, 36

6.3.8.2.1 Relief Valves 34, 116A

The schematic of relief valves 34 and 116A is shown in Figure 13. The body of these in-line valves is 316 SS with a neoprene O-ring inside the cylinder. The worst-case operating conditions of this valve are 120 °F (49 °C) and 70 psig (0.48 MPa) in both locations.

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Relief Valves #'s 34 and 116A	N	F	0	2	0	0	0	0	0	0	0	0	0	-	B
Relief Valve #22A	N	F	0	0	0	0	0	0	0	0	0	0	0	-	B
Relief Valve #31	F	F	3	0	0	3	0	0	0	0	0	0	0	-	B
Relief Valve #36	F	F	3	0	0	2	0	0	0	0	0	0	0	-	B

NOTES: Friction is present in both valves, but the metals are not flammable at the given pressures, making the frictional heating ignition hazard almost impossible.

Adiabatic compression is a possible source of ignition as a six to one pressure ratio may be generated. This rapid compression results in a 400+ °F (200+ °C) temperature rise (ASTM G 63). Neoprene has an AIT of less than 400 °F (Table 1), making it a likely candidate for ignition in this instance. However, pneumatic impact data indicates that neoprene samples of 50-60 mm thickness had zero ignitions in 20 impacts when tested at 250 °F (120 °C) and 135 psia (0.93 MPa).[1]

A mechanical impact ignition hazard is considered almost impossible because the spring forces are too low.

Particle impact is another almost impossible ignition source in these valves. Stainless steel is not flammable at the given temperature and pressure.

6.3.8.2.2 Relief Valve 22A

The schematic for relief valve 22A is shown in Figure 14. The body is aluminum, with a stainless steel spring and a neoprene O-ring. The environment surrounding this valve is less than 50 percent oxygen due to its location at the bottom of the nitrogen adsorber. The worst-case operating conditions include a temperature of 120 °F (49 °C) and a pressure of 77 psig (0.53 MPa).

NOTES: The aluminum materials are nonflammable in a 50-percent maximum oxygen environment (Worely, STP 1040.)

Frictional heating is present in this valve, but because the aluminum body is nonflammable, the ignition hazard is almost impossible.

Adiabatic compression is also an almost impossible source of ignition as its location (not downstream from a regulator) is distant from sources of rapid pressurization.

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[1] Unpublished WSTF Pneumatic Impact Test Data. NASA White Sands Test Facility, Las Cruces, NM.

Mechanical impact is another almost impossible ignition hazard. Spring forces are too low to cause ignition.

Again because the metals in this valve are nonflammable, ignition created by particle impact is almost impossible.

6.3.8.2.3 Relief Valve 31

The configuration of relief valve 31 is the same as relief valve 22A, shown in Figure 14, with an aluminum body, a stainless steel spring, and a neoprene O-ring. The surrounding environment, however, is 96 percent oxygen, located on the oxygen surge vessel. The worst-case operating temperature and pressure are 120 °F (49 °C) and 70 psig (0.48 MPa).

NOTES: The aluminum material in the valve, located in 96 percent oxygen, is considered flammable. The neoprene is also flammable under these conditions.

Frictional heating is a probable source of ignition because the aluminum parts are flammable. If stainless steel or brass were used, the ignition hazard would be almost impossible.

The spring forces are too low in this valve to cause ignition by mechanical impact. Therefore, the hazard rating is almost impossible.

Particle impact has a probable ignition hazard rating as trapped particles in the surge tank can cause ignition when impacting the aluminum body of the valve as it relieves. It is strongly recommended that the aluminum material in this valve be changed to stainless steel or brass.

6.3.8.2.4 Relief Valve 36

The schematic of relief valve 36 is also shown in Figure 14. This valve has the same configuration as relief valves 22A and 31 (aluminum body, aluminum poppet, stainless steel spring), only it has Viton® O-rings. The surrounding environment is also 96 percent oxygen. The worst-case operating conditions are 120 °F (49 °C) and 77 psig (0.53 MPa).

NOTES: As with relief valve 31, the aluminum materials are considered flammable under the given conditions.

Frictional heating is again a probable ignition source because the aluminum parts are flammable. The rating would drop to a zero if this material were changed to stainless steel or brass. It is strongly recommended to change the valve material to stainless steel or brass. Particle impact has an ignition hazard rating of possible in this valve. As with relief valve 31, particles trapped in the surge tank can impact the valve and cause ignition.

6.3.9 Check Valves 113, 100

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Check Valve #113	F	F	0	2	0	0	0	0	0	0	0	0	0	-	B
Check Valve #100	N	F	0	0	0	0	0	0	0	0	0	0	0	-	B

6.3.9.1 Check Valve 113

The schematic of check valve 113 is shown in Figure 15. A recent change in the material of this component, from aluminum to stainless steel and from neoprene to Viton®, now shows a stainless steel housing, spring, spring guide, and poppet with Viton® O-rings, and a Teflon® gasket. The worst-case operating conditions are 120 °F (49 °C) and 2,250 psig (15.5 MPa).

NOTES: Due to low spring forces and no cycling in the valve, frictional heating is an almost impossible ignition hazard.

Adiabatic compression, however, is a possible ignition source. Flow in the forward direction is not subject to rapid compression. But in reverse flow, adiabatic compression is possible from the 2,250 psig (15.5 MPa) source (the H-size cylinder). Viton® soft goods are flammable in the check valve if it gets rapidly pressurized, as during installation of the H-size cylinder. However, the fill procedures are computer controlled to prevent this from happening. In addition, a full cylinder, rather than a vented one, would have to be installed.

Particle impact is not an ignition hazard because the gas velocities through the check valve are too low.

6.3.9.2 Check Valve 100

The schematic of check valve 100 is shown in Figure 16. The valve body and internals are 316 SS with Viton® O-rings. The operating environment is 96 percent oxygen, with a possibility of gross contamination from the flex hose connecting the CFM to the OGDM. The worst-case operating temperature and pressure are 120 °F (49 °C) and 70 psig (0.48 MPa).

NOTES: Frictional heating is an almost impossible ignition source because of low spring forces and no cycling in the valve.

Adiabatic compression also has an almost impossible hazard rating. There is little chance that the valve will see backflow from the compressor.

Again, the oxygen gas velocities are too low to cause ignition from particle impact in the check valve. Thus, the particle impact hazard rating is zero.

6.3.10 High-Pressure Regulators 115, 38

The schematic for high-pressure regulators 38 and 115 is shown in Figure 17. This configuration has a stainless steel body, Viton® diaphragm and O-rings, and a Kel-F® 81 valve seat. The worst-case operating conditions for these regulators are 120 °F(49 °C) and 2,250 psig (15.5 MPa).

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
High Pressure Regulators 115 & 38	F	F	0	2	0	0	0	0	0	0	0	0	2	+	B

NOTES: Frictional heating is an almost impossible ignition hazard as long as the regulator is operating at a stable load.

Adiabatic compression has an ignition rating of possible. The only possibility for compressive heating to occur is at the seat of regulator, exposed to 2,250 psig (15.5 MPa). However, the regulators have a proven history of use (approximately 500 cycles of ambient to 2,000 psig (14 MPa) with no failures) and the pressurization rate is slow due to multi-turn valves on the backup cylinders. These factors reduce the hazard rating to two for this configuration. Also, the regulator diaphragm is protected by a 65 psig (0.45 MPa) setting to close.

Mechanical impact ignition is almost impossible due to small forces in the regulator.

Particle impact ignition is also almost impossible because of low velocities or filters placed upstream of the regulators.

The kindling chain hazard rating is possible. Toxicity is likely if the valve seat burns, possibly igniting other components downstream.

The secondary effects analysis concludes that further analysis is needed regarding the toxicity affect on patients if the Kel-F® 81 seat burns. If a fire does occur, patients who breathe the contaminated oxygen gas are at risk.

6.3.11 Mass Flow Controllers 44, 44B

The schematic for mass flow controllers 44 and 44B is shown in Figure 18. The body of the flow controller is 316 SS and the valve seat and O-rings are both Viton®. Worst-case operating conditions include a temperature of 120 °F (49 °C) through the main port and 180 °F (82 °C) maximum through the small capillary and a pressure of 70 psig (0.48 MPa). The flow rate is 3.5 ft^3/min (98 L/min) through the main port and 0.31 in^3/min (5 cc/min) through the small capillary.

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Mass Flow Controller #'s 44 & 44B	N	F	0	0	0	0	0	0	0	0	0	0	0	-	B

NOTES: Adiabatic compression is almost impossible as an ignition source because the pressure ratio of oxygen gas is too low.

Particle impact is not an ignition hazard because the stainless steel parts are nonflammable.

6.3.12 Manual Valves MV1(29A), MV2(29A), MV4(117), MV5(52C)

The schematic of manual valves MV1, MV2, MV4, and MV5 is shown in Figure 19. A 303 SS housing surrounds a 303 SS valve shaft, Viton® O-rings, and a Kel-F® 81 valve seat. The worst-case operating temperature and pressure are 120 °F (49 °C) and 2,250 psig (15.5 MPa).

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Manual Valves MV1, MV2, MV4, MV5	F	F	0	2	0	1	0	0	0	0	0	0	1	-	B

Note: Refer to #'s 29A, 117, and 52A

NOTES: In each of these valves, the gas velocities are too low for ignition to occur by frictional heating. Therefore, this ignition hazard rating is almost impossible.

Adiabatic compression is a possible ignition hazard. In most cases, though, pressurization rates in these applications are too low to cause an ignition. For MV1 and MV2, pressurization rates could be high when opening the valve on the opposite high-pressure storage bottle. However, this procedure has been performed several times without resulting in a fire. The fact remains that these valves are slow opening, which may explain why no ignitions have occurred.

Particle impact is only a remotely possible source of ignition. Particles are precluded by filters placed upstream of these valves or by pressure vessels. The type of particles potentially infiltrating this system typically do not cause ignition in stainless steel. When particle impact is evaluated for tolerance of gross contamination that may come from dirty quick disconnects, then this rating becomes a three, or probable, and requires a solution. One solution may be to add a filter at the quick disconnect or make the valve of nonflammable materials such as brass or Monel®.

6.3.13 Manual (Plug) Valve MV3 (29)

The schematic of manual valve 3 is shown in Figure 20. The body of MV3 is brass. It also has a 316 SS pin and a tetrafluoroethylene-coated Viton® O-ring. The worst-case operating conditions are 120 °F (49 °C) and 70 psig (0.48 MPa).

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Manual (Plug) Valve MV3	N	Y	0	0	0	0	0	0	0	0	0	0	0	-	A

Note: Refer to Item #29

NOTES: In this valve the pressures are too low to cause an ignition by adiabatic compression. Thus, adiabatic compression is an almost impossible ignition hazard.

Particle impact is also an almost impossible ignition source as the valve is filtered just upstream. Also, brass is not vulnerable to PIT ignition because it is nonflammable. (High-velocity Particle Impact Test results show that yellow brass (UNS C3600) did not completely burn at temperatures of up to 710 °F (380 °C) (Stoltzfus et al. 1988).

6.3.14 H-size Cylinder Fill Solenoid Valves 133, 115A

The schematic of the H-size cylinder solenoid valves is shown in Figure 21. The solenoid valves have a stainless steel body, guide, and plunger. The soft goods include a Kel-F® 81 poppet and a neoprene seal. The worst-case operating temperature and pressure are 120 °F (49 °C) and 2,250 psig (15.5 MPa), respectively.

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Solenoid Valves #'s 115A & 133	F	F	0	2	0	3	0	0	0	0	0	0	2	-	D

NOTES: The loads on these valves are too small for frictional heating to cause ignition. Therefore, the ignition hazard rating is zero.

Adiabatic compression is considered a possible ignition source. The scenario for pneumatic ignition in valve 115A is when an unvented H-size cylinder is connected to the fill port and opened. This pressurizes the valve rapidly. It is postulated that ignition has not occurred to date due to air being trapped in the line between the H-size cylinder and the valve, providing a buffer for rapid compression. Also, this scenario has occurred several times (50 to 150) without failure of the valve.

Particle impact is a probable ignition source in valve 115A. This rating could be lower if a filter is installed between the H-size cylinder connection and the valve.

A kindling chain ignition is possible as the Kel-F® 81 poppet can kindle a fire in the stainless steel body.

6.3.15 Solenoid Valves 136A, 33, and 100A

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Solenoid Valves #'s 33 & 136A	N	F	0	0	0	0	0	0	0	0	0	0	0	-	B
Solenoid Valve #100A	N	F	0	2	0	0	0	0	0	0	0	0	0	-	B

6.3.15.1 Solenoid Valves 136A and 33

The schematic for solenoid valves 136A and 33 is shown in Figure 22. The valves have a stainless steel body with neoprene O-rings and neoprene plunger inserts. The worst-case operating conditions are 120 °F (49 °C) and 70 psig (0.48 MPa) for both valves.

NOTES: Adiabatic compression is an almost impossible ignition hazard. Pressurization rates are too low in both of these valves.

Impact loads are also too low to cause an ignition in these valves. Therefore, the mechanical impact rating is zero.

Particle impact is an almost impossible source of ignition because the metals are not flammable.

Also because the metals in these valve are nonflammable, a kindling chain hazard is almost impossible.

6.3.15.2 Solenoid Valve 100A

The schematic of solenoid valve 100A is also shown in Figure 22. Its materials are the same as valves 136A and 33 (stainless steel and neoprene), but the operating conditions are different. The worst-case conditions are 120 °F (49 °C) and approximately 160 psig (1.1 MPa).

NOTES: Adiabatic compression is a possible ignition source in this valve as it is subject to rapid compression from the H-size cylinder. However, data from pneumatic impact tests show no ignitions at 1000 psi (6.9 MPa).[1] The impact loads in this valve are too low to cause an ignition by mechanical impact. Therefore, this hazard is considered almost impossible.

Particle impact is another almost impossible source of ignition because the metal parts of this valve are nonflammable at the given conditions.

6.3.16 High-Pressure Hoses and Quick Disconnects

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
High Pressure Hose	F	F	0	1	0	0	0	0	0	0	0	0	2	-	C
High Pressure Quick Disconnects	N	F	0	2	0	0	0	0	0	0	0	0	0	+	C

6.3.16.1 High-Pressure Hoses

The schematic for the high-pressure hoses is shown in Figure 23. The end fittings are made of 316 SS, the core tube is Nylon II and polyurethane. The worst-case operating conditions are 120 °F (49 °C) and 2,250 psig (15.5 MPa).

NOTES: When the hoses are connected to the system, pressurization rates are low, so the adiabatic compression ignition hazard is only remotely possible.

Particle impact is an almost impossible ignition source as velocities in the hose are too low to cause ignition.

Other ignition mechanisms are considered almost impossible. This assumes that no traffic will drive over the hoses. If there is a possibility of vehicles driving over the hoses, then the hazard rating increases to two. Driving over all oxygen hoses should be avoided. However, mechanical impact data indicates no ignitions since the gas velocities are too low to cause ignition 72 ft-lb (10 kg-m) at 125 psig (0.86 MPa) did not produce ignitions.[2]

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1 Unpublished WSTF Pneumatic Impact Test Data (WSTF 76-05857). NASA White Sands Test Facility, Las Cruces, NM.

2 Unpublished WSTF Mechanical Impact Test Data (WSTF 79-11263). NASA White Sands Test Facility, Las Cruces, NM.

6.3.16.2 Quick Disconnects for High-Pressure Hoses

The schematic for the quick disconnect is shown in Figure 24. For the high-pressure hoses, the body is currently made of stainless steel, but a decision has been made to change to plated brass. Therefore, this analysis will be for brass. All O-rings are Viton®. The worst-case operating conditions include ambient temperature and a pressure of 2,250 psig (15.5 MPa).

NOTES: Adiabatic compression is a possible ignition source in the quick disconnect. This hazard rating would increase to *probable* if the upstream manual valve, MV4, is opened when the flex hose is disconnected. The likelihood of this happening at the CFM connection is low. Also, if a fire does occur, it will not kindle in the brass quick disconnect body. On the OGDM side, this has been done often without resulting in fire. Therefore, the hazard rating is only *possible.*

Particle impact ignition is considered an almost impossible ignition source because the brass body is not vulnerable.

The secondary effects analysis shows that the quick disconnects are a highly likely point of entry for contaminant into the system. If gross contaminant does enter the system, then the quick disconnects, the hose, the high-pressure storage cylinders, and the bottle valves are all affected. On performing further analysis, the quick disconnect is considered to be tolerant of contamination hazards, the hose is also tolerant, the cylinders are tolerant, and the valves are tolerant as well.

6.3.17 Low-Pressure Hoses and Quick Disconnects

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Low Pressure Hoses	N	F	0	1	0	0	0	0	0	0	0	2	0	+	B
Low Pressure Quick Disconnects	N	F	0	0	0	0	0	0	0	0	0	0	0	+	B

6.3.17.1 Low-Pressure Hoses

The schematic for the low-pressure hoses is shown in Figure 23. The configuration and materials in these hoses are the same as in the high-pressure hoses. The worst-case operating conditions are 120 °F (49 °C) and 70 psig (0.48 MPa).

This analysis also applies to all low-pressure oxygen distribution hoses in the field hospital which are PVC instead of nylon. PVC performs better than nylon with respect to ignition and combustion resistance, and its operating conditions (in the hospital) are less severe.

NOTES: Adiabatic compression in the low-pressure hoses is a remotely possible ignition hazard. Pneumatic impact data for Nylon 66 indicates no ignitions in pressures less than or equal to 250 psig (1.7 MPa).[1]

The velocities in the low-pressure hoses are too low to create an ignition hazard by particle impact. Particle impact data at 72 ft-lb at 125 psig shows no ignitions.[2] Therefore, the ignition hazard is almost impossible.

Another ignition mechanism for these hoses is being driven over. Like the high-pressure hoses, the low-pressure hoses are subject to vehicle traffic. Driving over the hoses should be avoided despite mechanical impact data which shows no ignitions (See note on particle impact above).

The secondary effects analysis indicates further analysis is needed on the effects of driving over the low-pressure hoses. If a hose is severed by a vehicle, oxygen enrichment in the vehicle could cause a fire. It is imperative to preclude vehicle traffic on all oxygen hoses.

The reaction effects assessment is marginal. If a low-pressure hose ruptures, backups are available. Also, the system is designed to be able to handle a ruptured hose. If a fire occurred in a low-pressure hose, it is unlikely that the fire would travel down the hose to affect other components.

6.3.17.2 Quick Disconnect for Low-Pressure Hoses

The schematic for these quick disconnects is shown in Figure 24. The configuration for the low-pressure quick disconnects is the same as for the high-pressure quick disconnects except the body is 316 SS instead of brass. The worst-case operating temperature and pressure are 120 °F (49 °C) and 70 psig (0.48 MPa), respectively.

NOTES: The pressure ratio is too low in this component to cause ignition by adiabatic compression. Therefore, the hazard rating is zero.

Particle impact is an almost impossible ignition hazard because the 316 SS body is not flammable under the given conditions.

The secondary effects analysis shows that the quick disconnects are a highly likely place for contaminants to enter the system. If gross contamination enters the system here, then the hose, opposing quick disconnect, and check valve 100 (CFM inlet), are affected. Both the quick disconnect and check valve 100 are tolerant of gross contaminant.

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1 Unpublished WSTF Pneumatic Impact Test Data (WSTF 81-13864). NASA White Sands Test Facility, Las Cruces, NM.

2 Unpublished WSTF Mechanical Impact Test Data (WSTF 79-11263). NASA White Sands Test Facility, Las Cruces, NM.

6.3.18 Flex Hose to H-size Cylinder

The configuration and materials in this hose are identical to the low-pressure hose, Figure 23. The worst-case operating conditions are 120 °F (49 °C) and 2,250 psig (15.5 MPa), respectively.

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Flex Hose to H-F Cylinder	F	F	0	1	0	0	0	0	0	0	0	0	2	-	C

NOTES: Compression heating only occurs in this flex hose when a pressurized cylinder is incorrectly installed to the system. In this situation, the oxygen gas is contained within stainless steel hardlines. For this reason, adiabatic compression is only a remotely possible ignition source.

6.3.19 Booster Inlet Regulator 52AA, Product Pressure Regulator 35

The schematics of regulators 52AA and 35 are shown in Figures 25 and 26, respectively. Each has an aluminum body with a Buna-N® diaphragm. The worst-case operating temperature is 120 °F (49 °C) for both regulators. The worst-case operating pressure for 52AA is 70 psig (0.48 MPa) and for 35 is 35 psig (0.24 MPa).

NOTES: If in fact, these regulators are as specified, then they are not appropriate for use in an oxygen system. They present an extreme fire hazard to this system. It is strongly recommended to change the regulators such that their materials are compatible with oxygen.

No analysis is done on these components, plan to change materials as needed.

6.3.20 Backup Oxygen Valve 37

The schematic of the backup oxygen valve is shown in Figure 27. The valve has a 303 SS body, Viton® O-rings, and a Kel-F® 81 seal. The worst-case operating temperature and pressure are 120 °F (49 °C) and 70 psig (0.48 MPa) from both ports of the valve.

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Backup Oxygen Valve #37	N	F	0	0	0	0	0	0	0	0	0	0	0	-	B

NOTES: The metals in this valve are nonflammable, so frictional heating is an almost impossible ignition source.

Adiabatic compression is not a hazard issue because the pressure ratios in the valve are too low.

Mechanical impact is also an almost impossible ignition hazard. Though the stem of the valve is hitting its seat, the resultant energies are too low to cause an ignition.

The particle impact hazard rating is almost impossible. The metals in this valve are nonflammable.

6.3.21 Constant Purge Valve 25

The schematic of the constant purge valve is shown in Figure 28. This valve currently has a stainless steel housing, but this will change to brass. Analysis is performed as if component is brass. The O-rings are fluorocarbon (per MIL-R-83248) and each port contains a brass reducer bearing. The worst-case operating conditions are 120 °F (48 °C) and 35 psig (0.24 MPa).

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Constant Purge Valve #25	N	F	0	0	0	0	0	0	0	0	0	0	0	-	A

NOTES: Particle impact is an almost impossible ignition source because the metals in the valve are nonflammable.

6.3.22 Purge Control Valve 24 and Manifold

6.3.22.1 Purge Control Valve 24

The schematic for the purge control valve is shown in Figure 29. The valve body is passivated 430 SS with a Buna-N® bottom seal and Buna-N® O-rings. Worst-case operating conditions include a temperature of 120 °F (48 °C) and a pressure of 35 psig (0.24 MPa).

NOTES: The pressure ratios in the purge control valve are too low to create an ignition by adiabatic compression. Therefore, the hazard rating is a zero.

The energies are too low to fear mechanical impact as an ignition hazard (High-pressure gaseous oxygen mechanical impact test results show zero out of 20 ignitions for a 3.81-mm (0.15-in.) Buna-N® sample at 1,500 psia (10.3 MPa) and 20.2 lbm-ft (2.8 kg-m) (Bryan 1991)).

Particle impact is considered an almost impossible ignition source because the metals are nonflammable.

A kindling chain ignition is also considered almost impossible because the metals are nonflammable.

6.3.22.2 Purge Control Valve Manifold

The schematic of the purge control valve manifold is shown in Figure 30. It has an aluminum housing and Buna-N® O-rings. Worst-case operating conditions include a temperature of 120 °F (48 °C) and a pressure of 35 psig (0.24 MPa).

NOTES: The Al 6061-T6 housing is considered flammable if ignited in this setting. The Buna-N® O-rings are also flammable if ignited.

The gas velocities in the manifold are too low to create an ignition hazard by particle impact. Thus, this hazard rating is zero.

6.3.23 Equalization Valve 23

The schematic of the equalization valve is shown in Figure 31. The materials consist of an anodized aluminum housing and Viton® O-rings. The worst-case operating conditions for this valve include a temperature of 120 °F (49 °C) and a pressure of 35 psig (0.24 MPa).

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Equalization Valve #23	N	F	0	0	0	0	0	0	0	0	0	0	0	-	A

NOTES: The anodized aluminum in the equalization valve is considered nonflammable under the given conditions (Zabrenski et al, STP 1040, STP 986).

The pressure ratios through this valve are too low for adiabatic compression to become an ignition hazard.

Because the metals in the valve are nonflammable, particle impact is an almost impossible source of ignition.

6.3.24 Product Filters 101 and 43, with Bleed Valves

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Filter #'s 101 & 43	F	F	0	0	0	0	0	0	0	0	0	0	2	-	C
Bleed Valve for Filter #'s 101 & 43	N	F	0	0	0	0	0	0	0	0	0	0	0	-	B

6.3.24.1 Product Filters 101 and 43

The schematic of product filters 101 and 43 is shown in Figure 32. The body is anodized aluminum; the internal and external support sleeves are carbon steel; the filter material is borosilicate glass fiber. The element filtration rating is 0.01 micron with 99.9999 percent efficiency. The worst-case operating conditions are 120 °F (49 °C) and 77 psig (0.53 MPa).

NOTES: The gas velocities are too low through these filters to cause an ignition by particle impact. Therefore, the hazard rating is almost impossible.

Kindling chain is a possible ignition hazard only because filter materials like aluminum are very flammable and could cause the carbon steel parts to burn if ignited. However, no credible ignition sources in the filter are identified.

6.3.24.2 Bleed Valve for Product Filters 101 and 43

The schematic for the bleed valves of these two filters is also shown in Figure 32. The bleed valves are made of brass and are exposed to the same operating conditions as the filter itself (120 °F (49 °C) and 77 psig (0.53 MPa)). The maximum flow rate through the bleed valve is 200 ft^3/h (6 m^3/h).

NOTES: Adiabatic compression is an almost impossible ignition hazard because the gas flow rate is diminished by the large volume of the filter housing.

Particle impact is not an ignition source because the valve material (brass) is nonflammable.

Kindling chain is also an almost impossible ignition hazard because the brass valve is nonflammable.

6.3.25 Vacuum Compressor 134

The schematic of the vacuum compressor is shown in Figure 33. The valve plate, head, piston and connecting tube are die cast aluminum. The O-ring seals are filled Teflon® and Buna-N®. The worst-case operating conditions are 120 °F (49 °C) and 50 psig (0.34 MPa).

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Vacuum Compressor #134	F	F	2	0	0	0	0	0	0	0	0	0	2	-	B

NOTES: The aluminum metal is considered flammable because the source of oxygen is cylinders which may not have an argon-oxygen mix.

Frictional heating is a possible ignition source in the vacuum compressor. If the piston seal fails, then friction will be present, creating heat. However, if solenoid valve 100A is reset to 20 psi, then the aluminum is nonflammable and friction decreases.

The pressure ratios are too low in the compressor to create an ignition hazard by adiabatic compression.

A kindling chain ignition is possible, but no ignition mechanisms are identified for the polymers. Also, a limited source of oxygen exists in the compressor to support combustion.

6.3.26 Oxygen Filter 132

The schematic of the oxygen filter is given in Figure 34. The filter is 304 SS throughout. The worst-case operating conditions include a temperature of 120 °F (49 °C) and pressure of 2250 psig (15.5 MPa).

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Oxygen Filter #132	F	-	0	0	0	0	0	0	0	0	0	0	0	+	B

NOTES: There are no soft goods in this filter.

The gas velocities in the filter are extremely low. Thus, an ignition by particle impact is almost impossible.

A secondary effects analysis on the filter shows that, if a filter breaks, it can create an ignition hazard in downstream components. A consistent filter maintenance program is important for this oxygen filter.

6.3.27 Hardlines for OGDM and CFM

All hardlines in the CFM are made of 304 SS. The OGDM has 304 SS lines as well as Al 5052-0 and Al 6061-T6. The worst-case operating conditions for the hardlines are 120 °F (49 °C) and 2,250 psig (15.5 MPa).

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Hardlines	F	-	0	0	0	0	0	0	0	0	0	0	0	-	C

NOTES: The particle impact hazard rating is almost impossible. The velocity in 0.25 x 0.049 in. (0.64 x 0.12 cm) hardlines is less than 5 ft/s (1.5 m/s) during pumping from the compressor. The maximum velocity in the hardlines during venting of the cylinders is less than 25 ft/s (7.6 m/s) (manufacturer specifications). These low velocities are unlikely to create an ignition by particle impact.[1]

6.3.28 Temperature Indicators 112, 112B-F

The schematic of the temperature indicators is shown in Figure 35. The sheath material is 304 SS. The worst-case operating conditions include a temperature of 300 °F (150 °C) and a pressure of 2,250 psig (15.5 MPa).

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Temperature Indicators #'s112 & 112B-F	F	-	0	0	0	0	0	0	0	0	0	0	0	-	A

NOTES: The stainless steel sheath is flammable under the given conditions. There are no soft goods considered part of the indicators.

No ignition hazards are identified for these components.

6.3.29 Oxygen-Enriched Atmosphere (OEA) in Cabinet

The housing of the cabinet is all carbon steel. It contains plastic insulation, coatings, and relay bodies. The worst-case operating conditions include a temperature of 300 °F (150 °C) and a pressure of 2,250 psig (15.5 MPa).

[1] Unpublished WSTF Particle Impact Test Data. NASA White Sands Test Facility, Las Cruces, NM.

	Metal	Soft Goods	Frictional Heating	Adiabatic Compression	Mechanical Impact	Particle Impact	Mechanical Stress	Static Discharge	Electrical Arc	Chemical Reaction	Resonance	Other Ignition Mechanisms	Kindling Chain	Secondary Effect	Reaction Effect
Oxygen Enriched Atmosphere (OEA) in Cabinet	N	F	0	0	0	0	0	0	2	0	0	0	0	-	B

NOTES: The soft goods are considered flammable in the cabinet in the case of oxygen enrichment. The soft goods include insulation, coatings, and relay bodies.

Electrical arc is a possible ignition source in the cabinet. The motor is nonsparking, which makes this hazard less severe. Also, the electrical relays are in a separate compartment and the effects of a fire are not catastrophic.

The secondary effects analysis shows no further analysis is needed. If electrical relays are damaged, then the system fails without catastrophic results.

7.0 Recommendations

The following are recommendations made by the Oxygen Hazards Analysis Team concerning components in the FMOGDS.

7.1 High-Pressure Cylinder in the Oxygen Compressor Assembly

Frictional heating is a probable cause of ignition in this cylinder. If a normal force of approximately 80 lbf (360 N) can be generated, then a hazard exists. This could result from a bent shaft being used in the cylinder. **Recommendation** is to prove that such a normal force cannot be generated and/or proper assembly procedures do not allow a bent shaft to be admitted into the compressor.

7.2 3-Way Valve on CFM Manifold Assembly

Particle impact is a probable cause of ignition with the polymer seat. **Recommendation** is to keep particles out of the valve by installing a filter upstream from this valve, near the cylinder clamp assembly. Filter implementation is currently planned. Also, kindling chain is probable between the Vespel® seat and the SS 316 pin. **Recommendation** is to replace this stainless steel with a nonflammable metal such as brass or Monel® to eliminate this hazard.

7.3 Relief Valve 31

Frictional heating is a probable ignition source because of the valve's aluminum parts. **Recommendation** is to replace the aluminum parts with a nonflammable metal such as stainless steel or brass. Particle impact is also a probable ignition source if particles get trapped in the surge tank. **Recommendation** is to install a filter between this relief valve and the oxygen surge vessel.

7.4 Relief Valve 36

Frictional heating is a probable source of ignition, because of the valve's aluminum parts. **Recommendation** is to replace aluminum parts with a nonflammable metal such as stainless steel or brass.

7.5 Manual Valves MV1, MV2, MV4, MV5

When evaluated for tolerance of gross contamination that may come from dirty quick disconnects, then particle impact becomes a probable ignition source in these valves. **Recommendation** is to install a filter at the quick disconnects or to make the valve of nonflammable metals such as brass or Monel®.

7.6 H-size Cylinder Fill Solenoid Valve 115A

Particle impact is a probable source of ignition as the valve is unprotected. **Recommendation** is to install a filter between the valve and the H-size cylinder connection.

7.7 Product Pressure Regulator 35, Booster Inlet Regulator 52AA

Both of these regulators contain materials that are completely inappropriate for use in oxygen systems. No analysis was attempted on these components. **Recommendation** is to immediately replace both regulators with oxygen-compatible components.

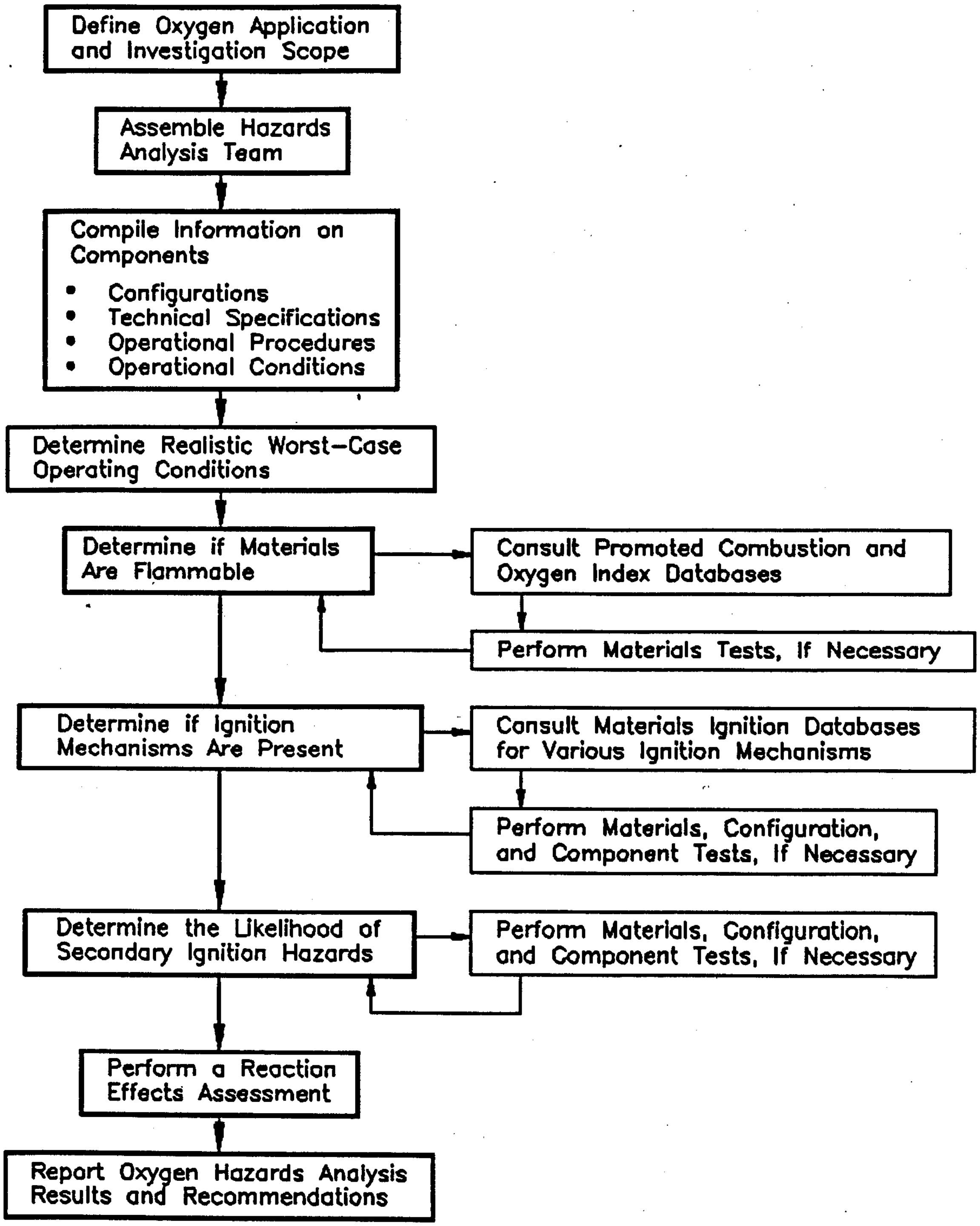

Figure 1
Approach to Oxygen Hazards Analysis

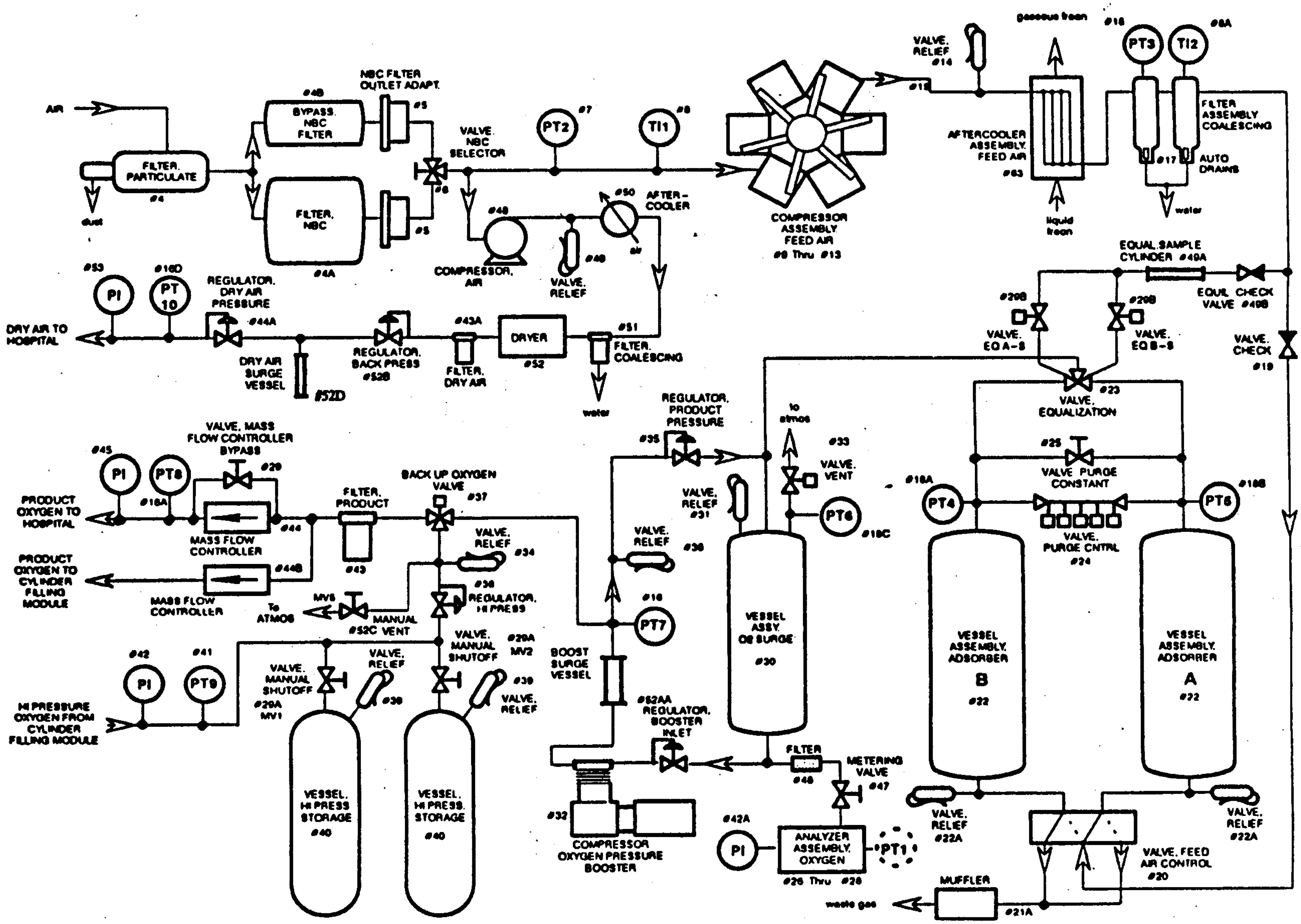

Figure 2
Process Flow Diagram of the Oxygen Generation Distribution Module

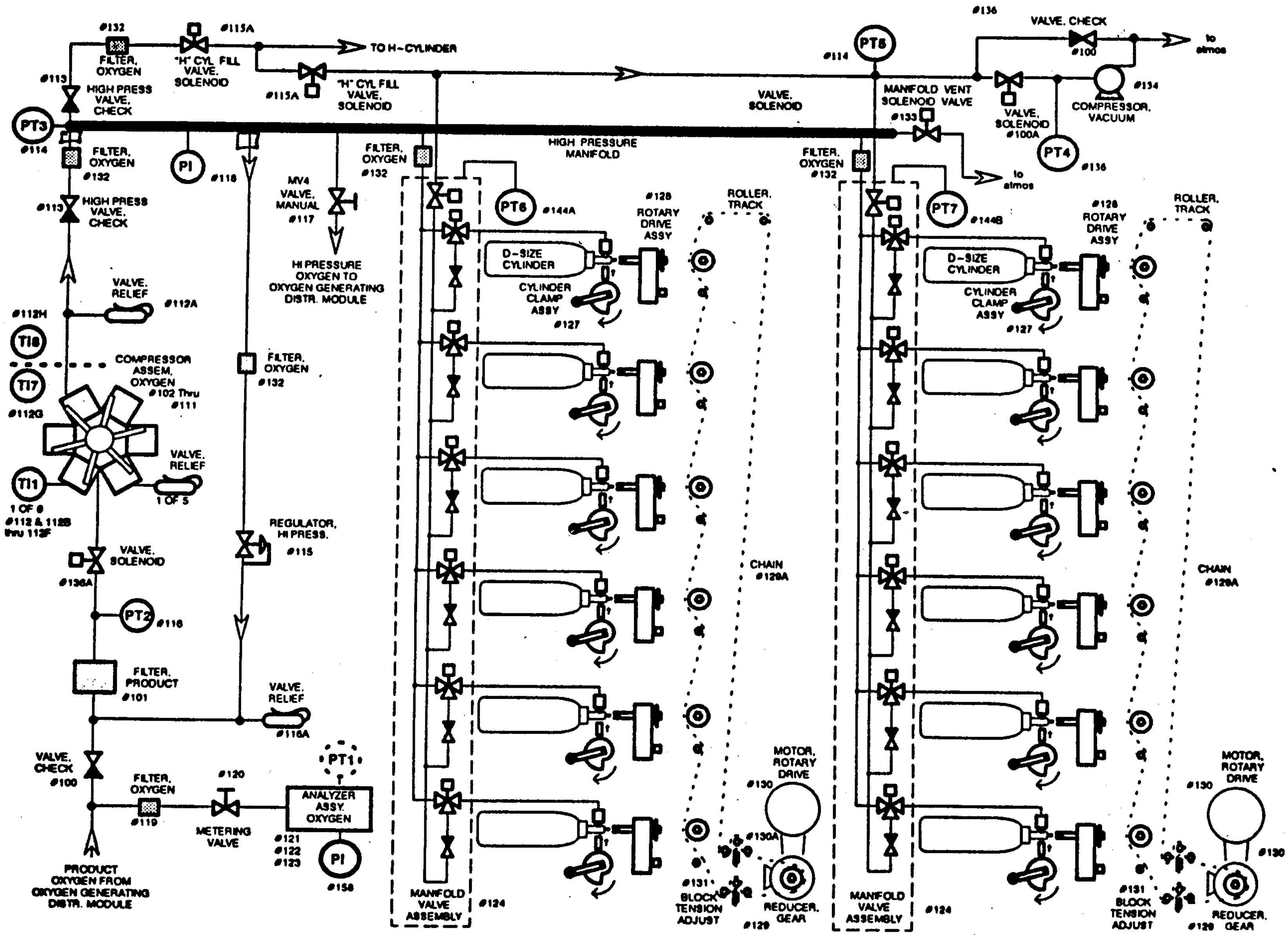

Figure 3
Process Flow Diagram of the Cylinder Filling Module

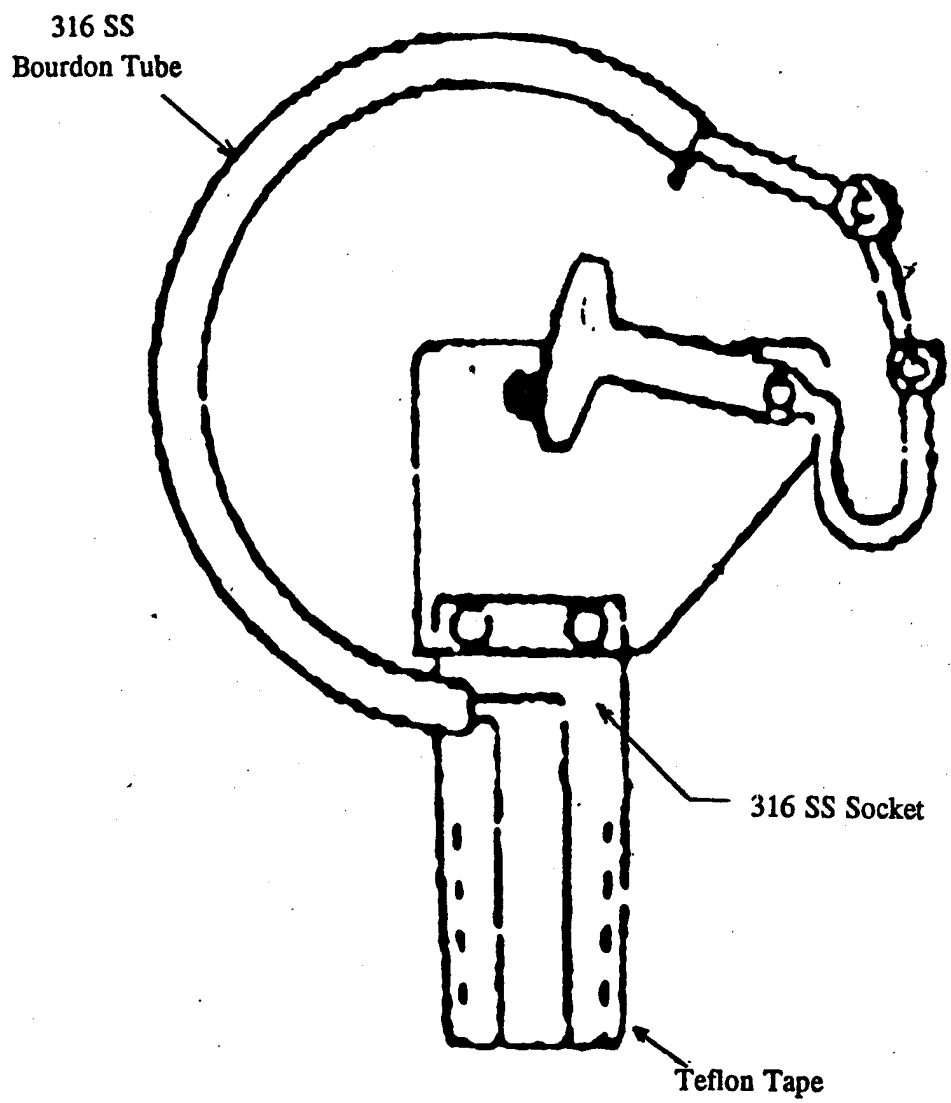

Figure 4
Pressure Gauges 42, 45, and 118

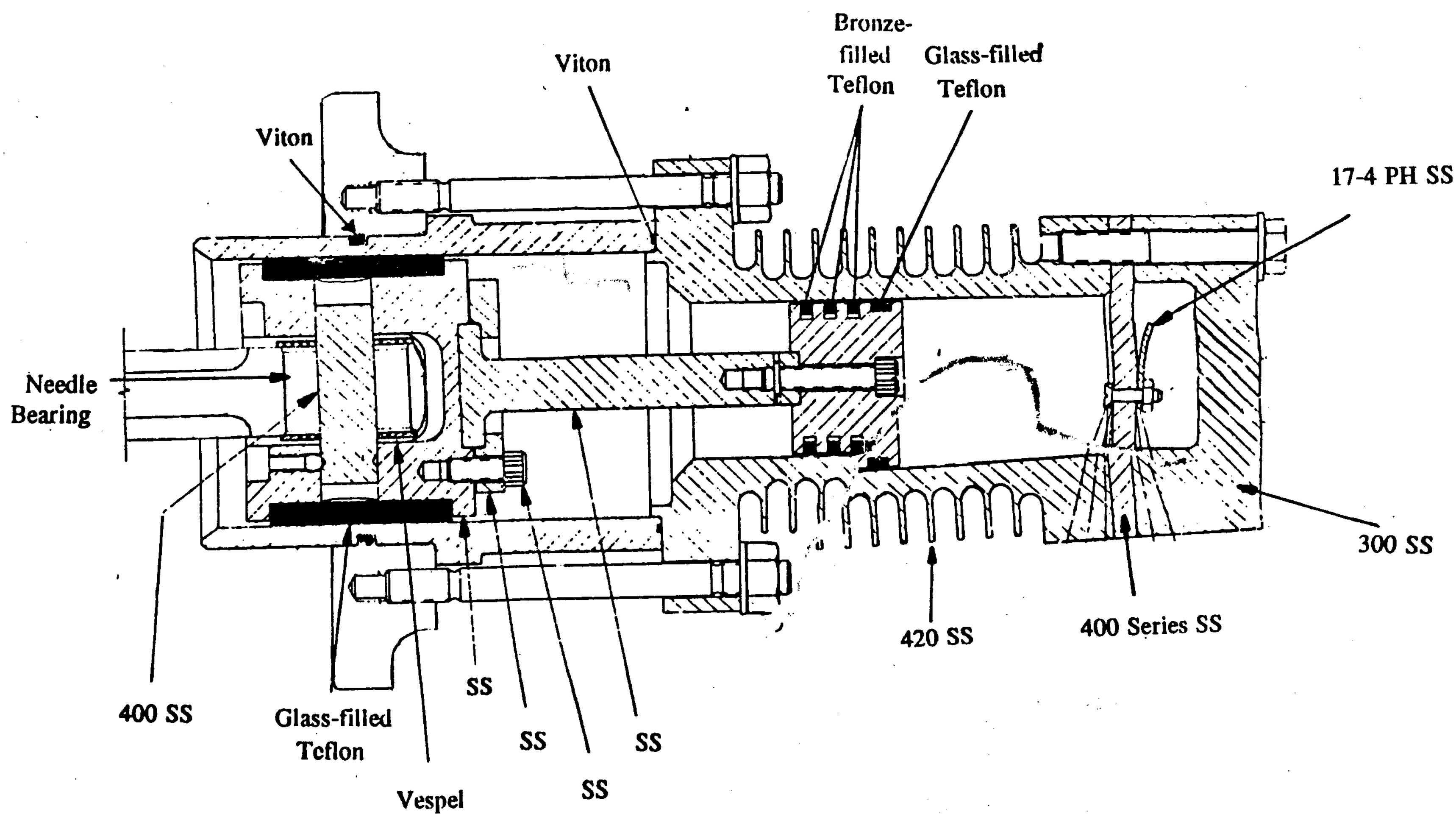

Figure 5a
Low-Pressure Cylinder of Oxygen Compressor

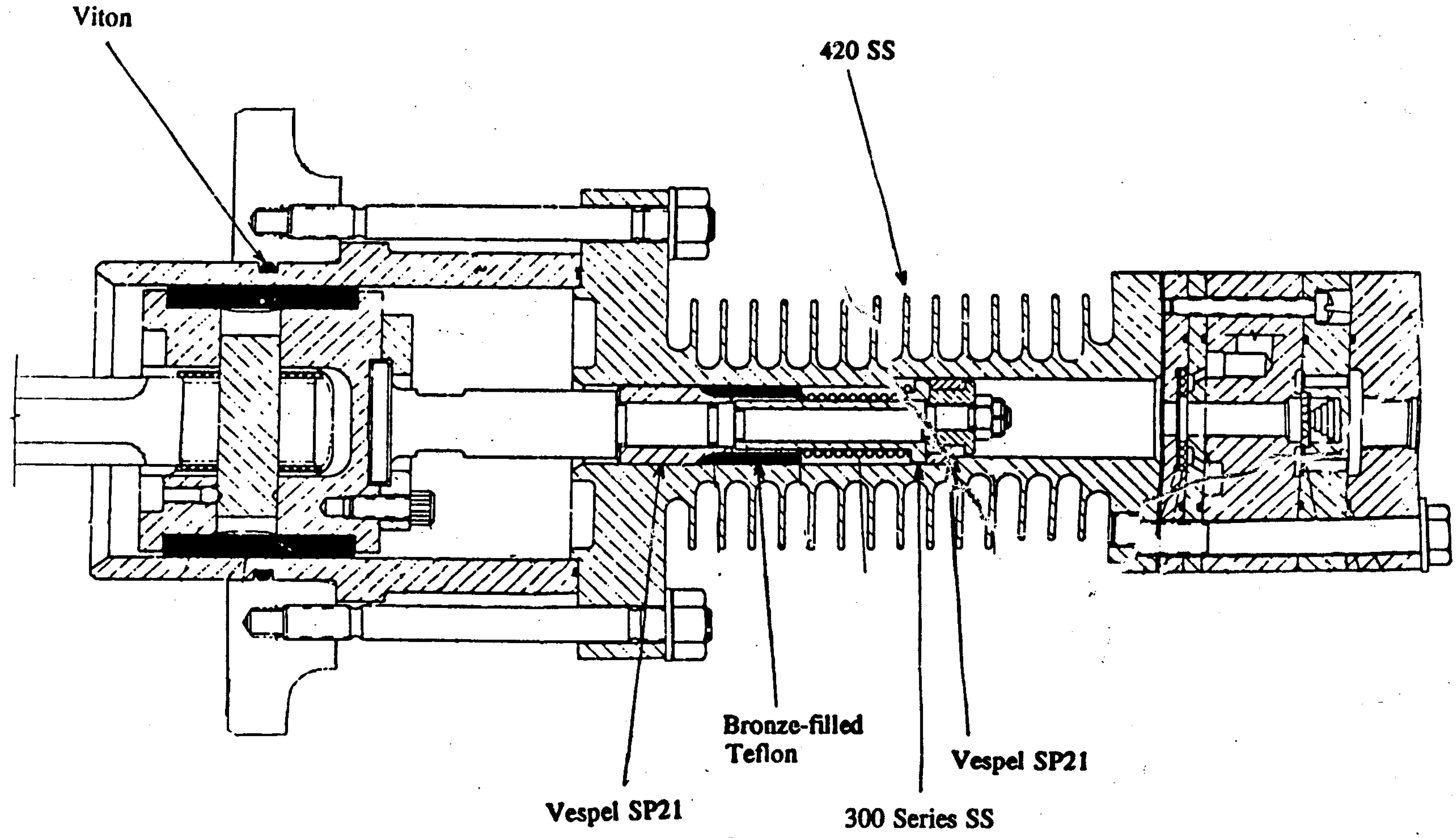

Figure 5b
Mid-Pressure Cylinder of Oxygen Compressor

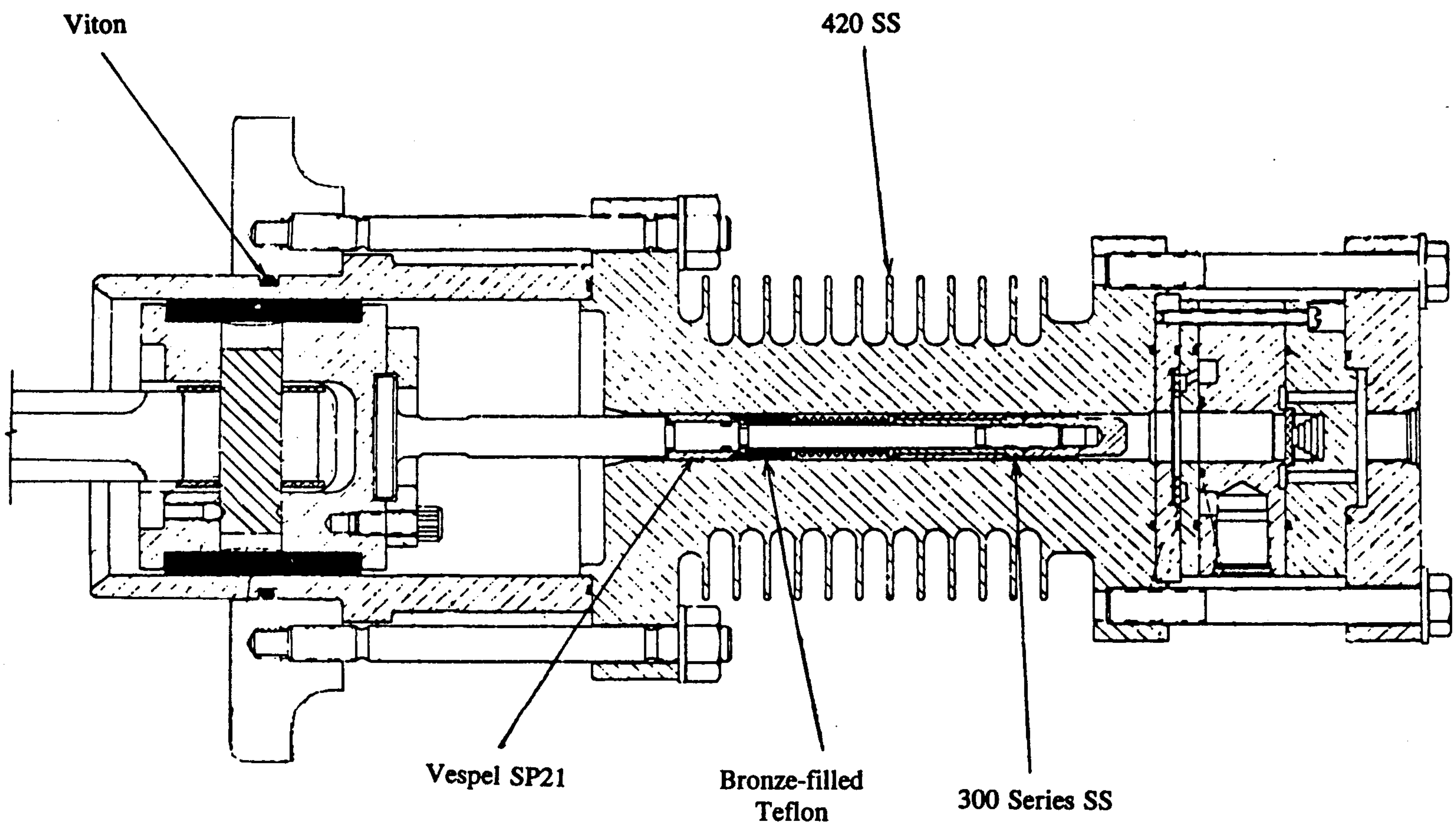

Figure 5c
High-Pressure Cylinder of Oxygen Compressor

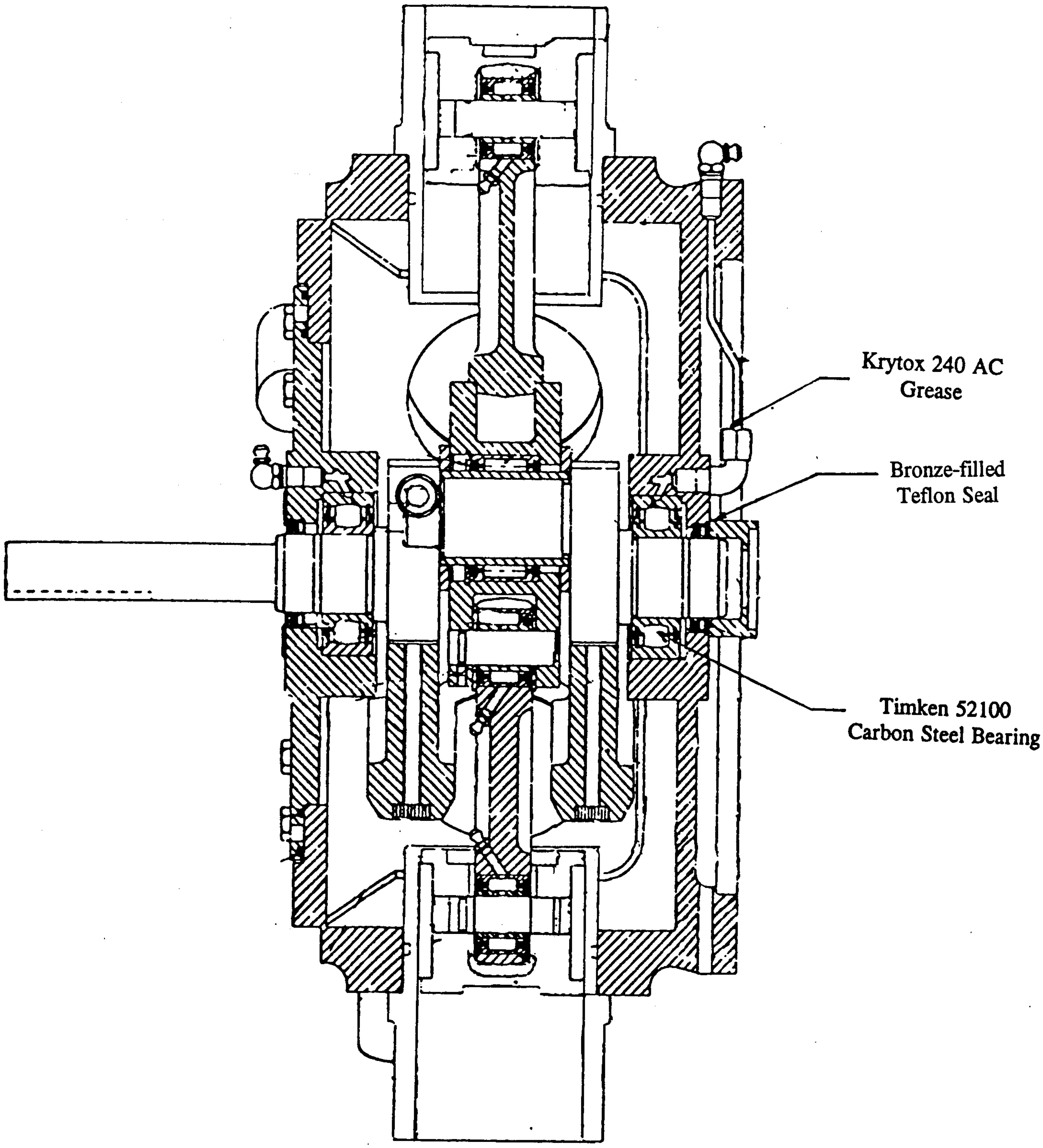

Figure 5d
Frame and Running Gear of Oxygen Compressor

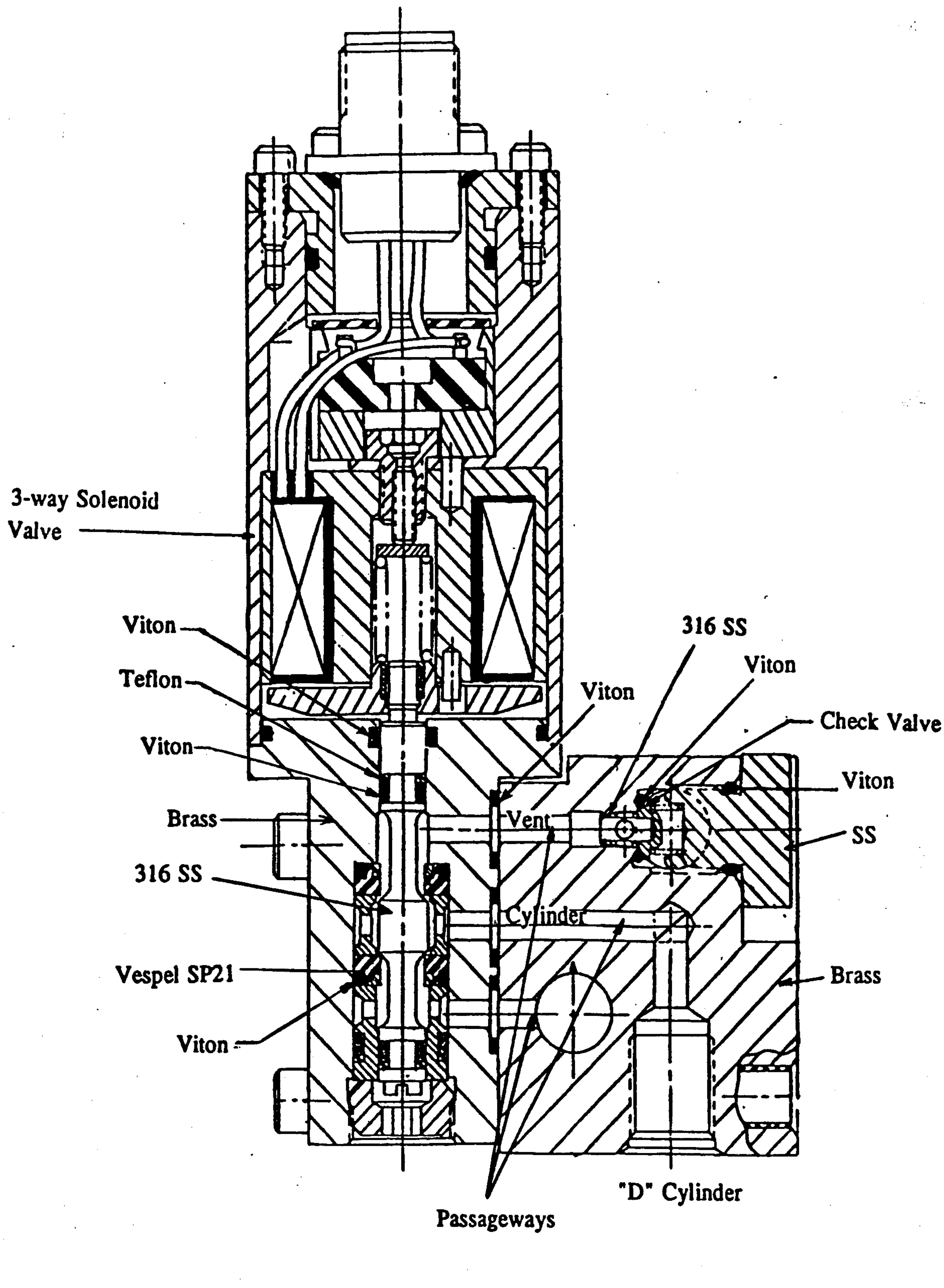

Figure 6
Manifold Valve Assembly 124

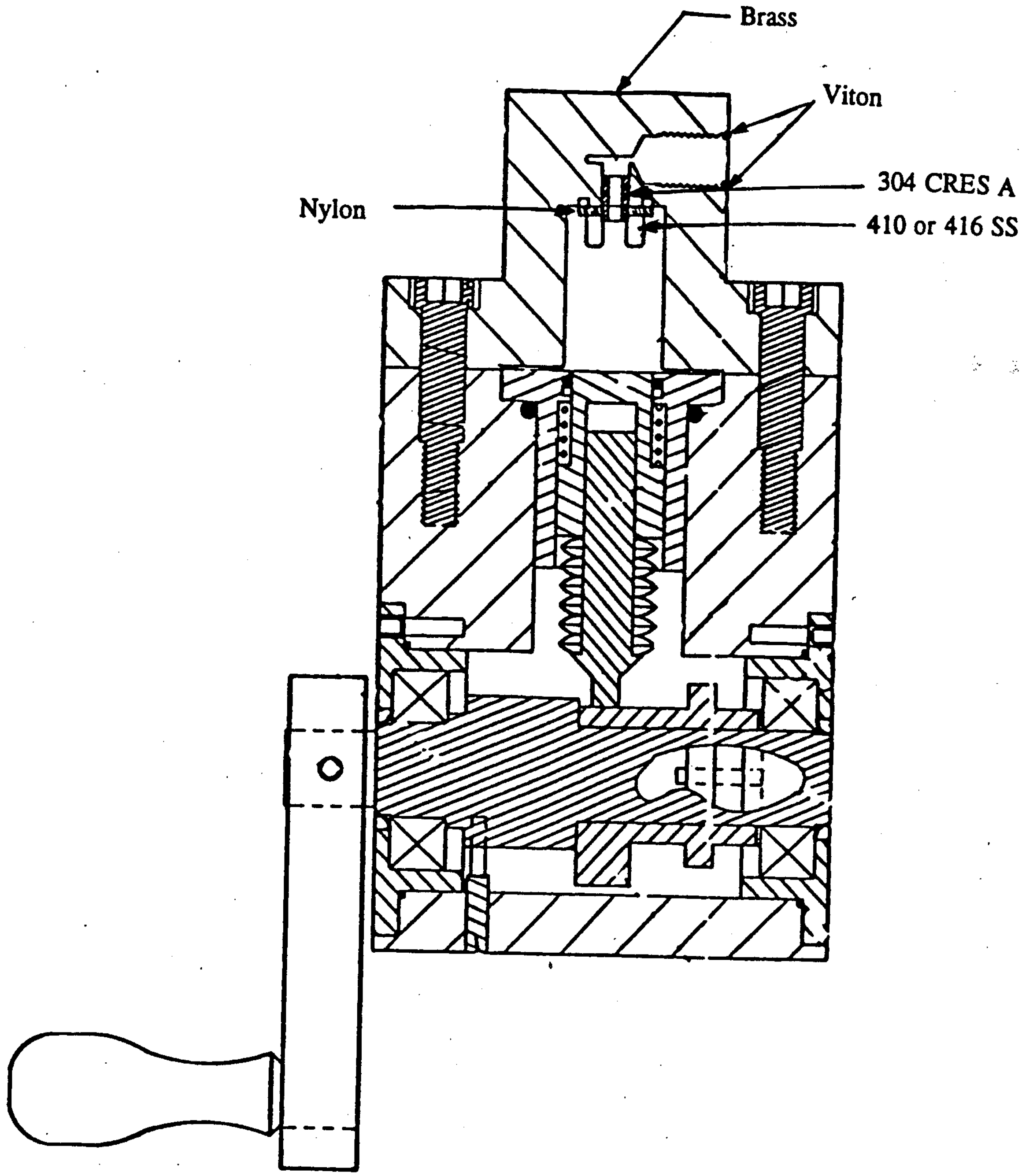

Figure 7
Cylinder Clamp Assembly 127

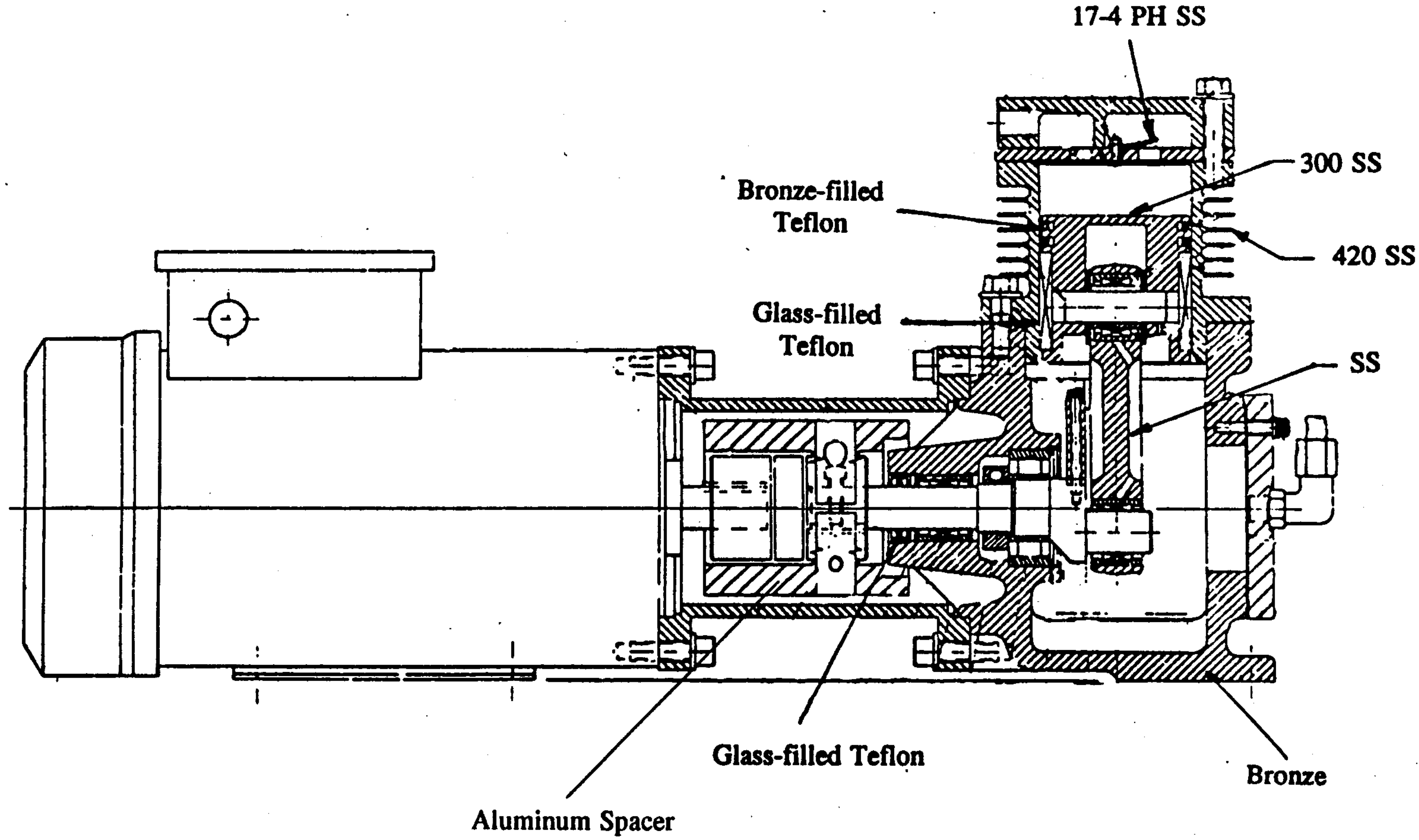

Figure 8
Low-Pressure Booster Pump 32

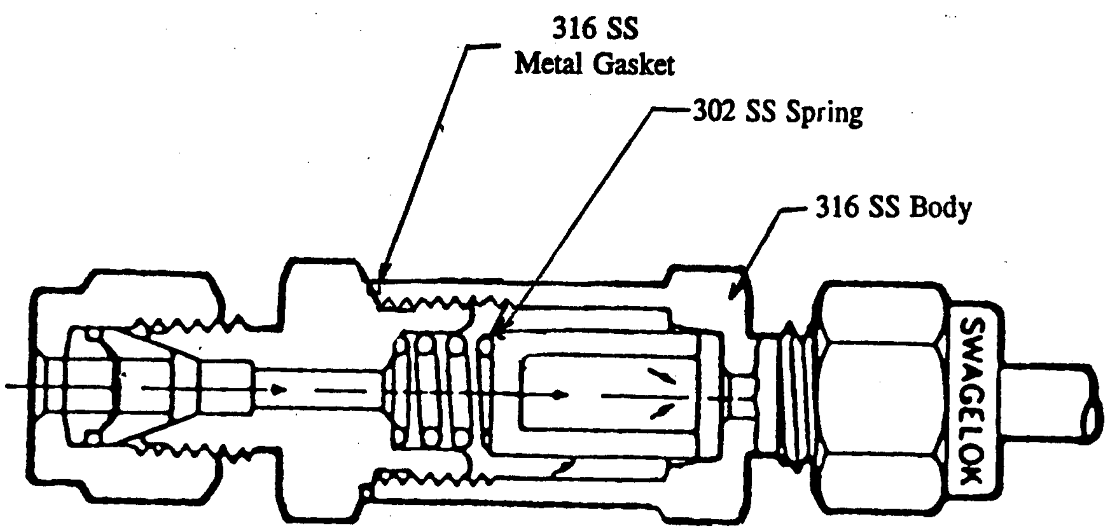

Figure 9
Oxygen Filters 46 and 119

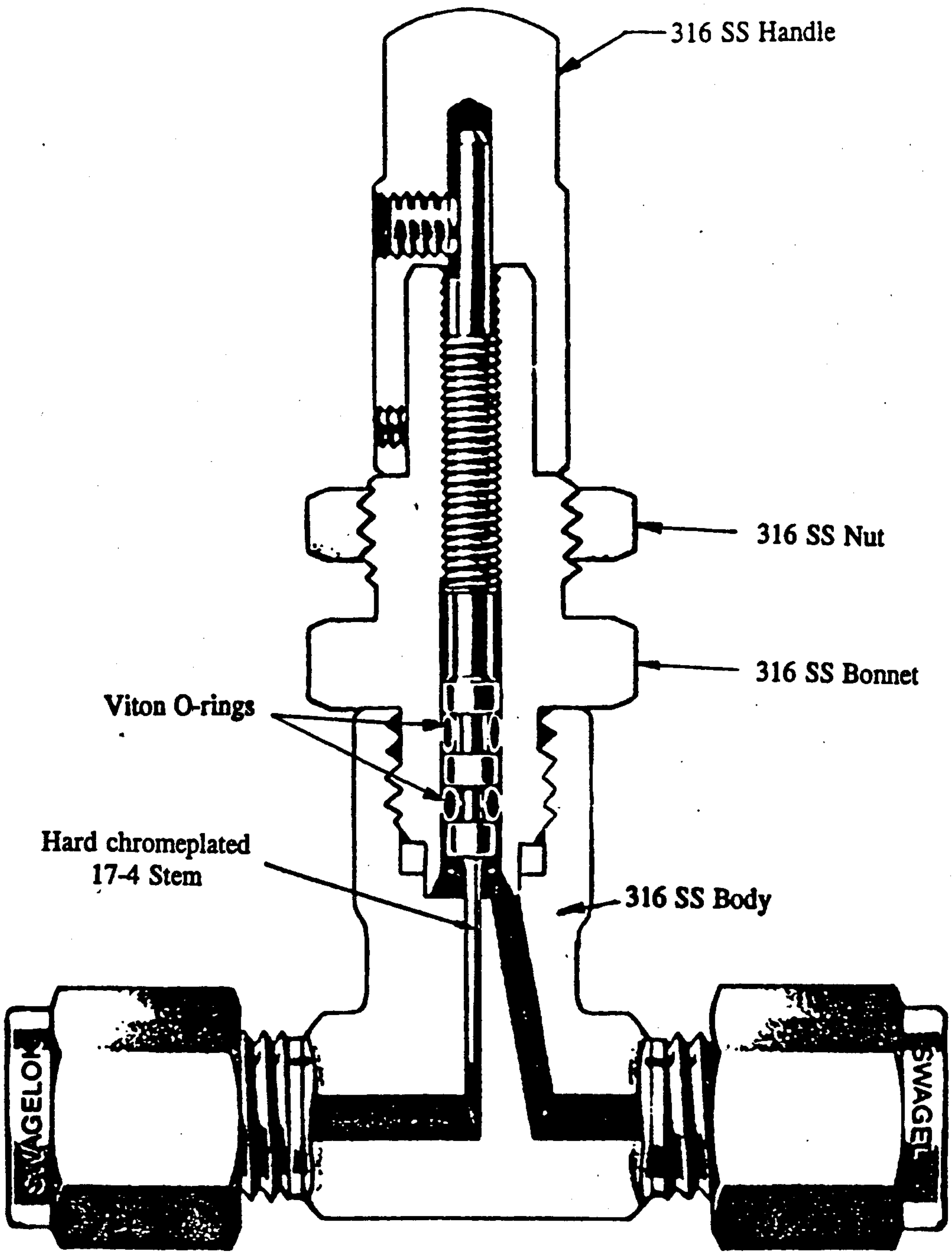

Figure 10
Oxygen Metering Valves 47 and 120

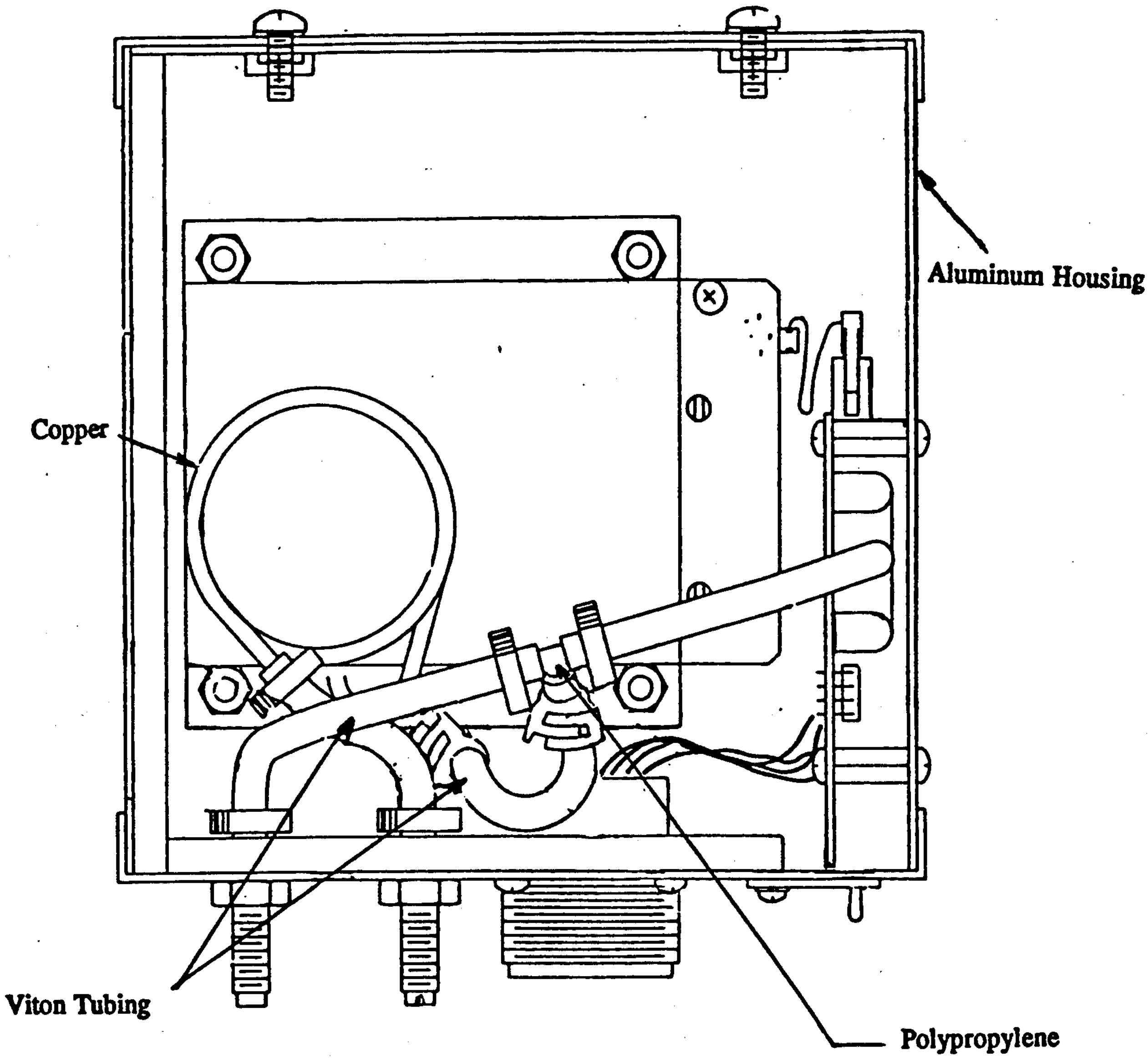

Figure 11
Oxygen Analyzer Assemblies 21 through 28 and 121 through 123

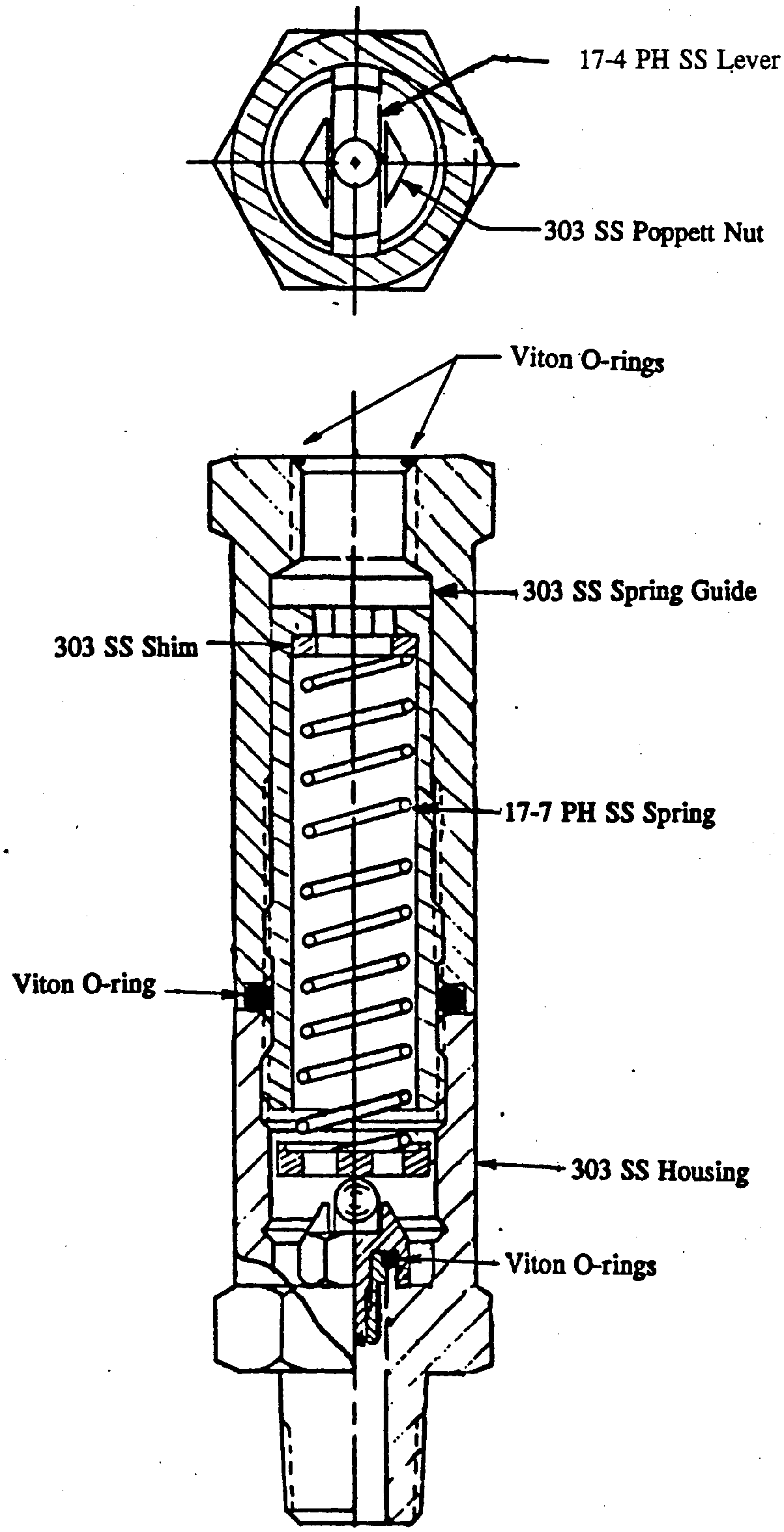

Figure 12
Relief Valves 39 and 112A

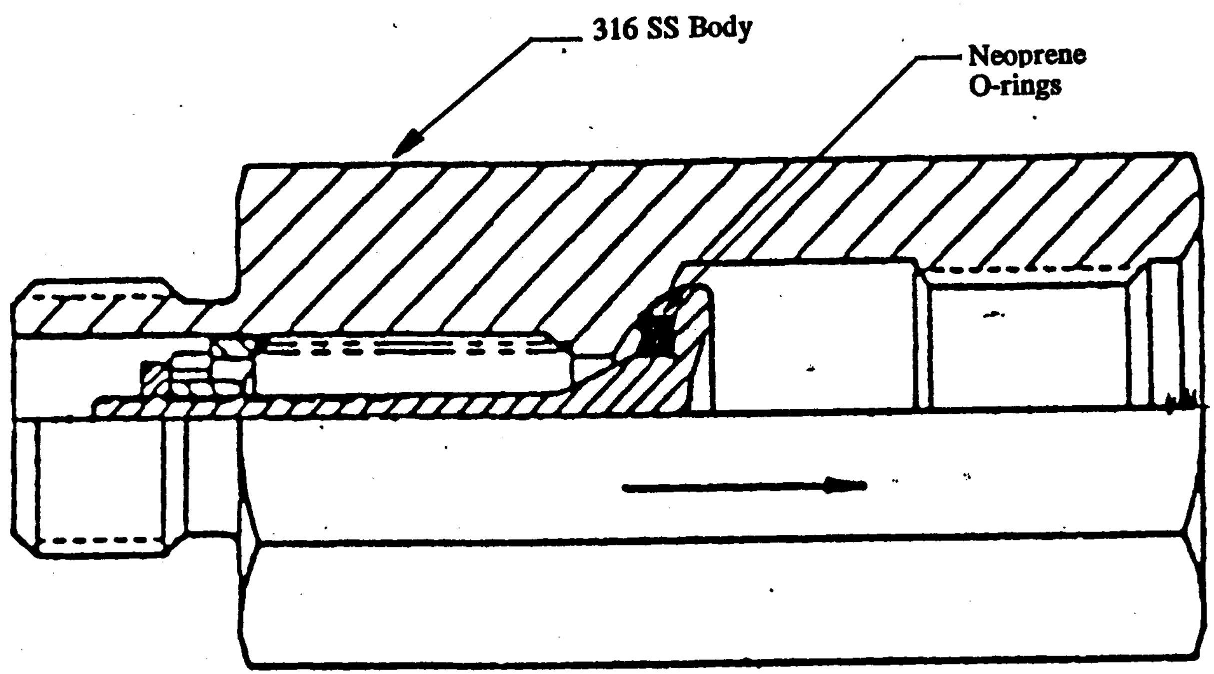

Figure 13
Relief Valves 34 and 116A

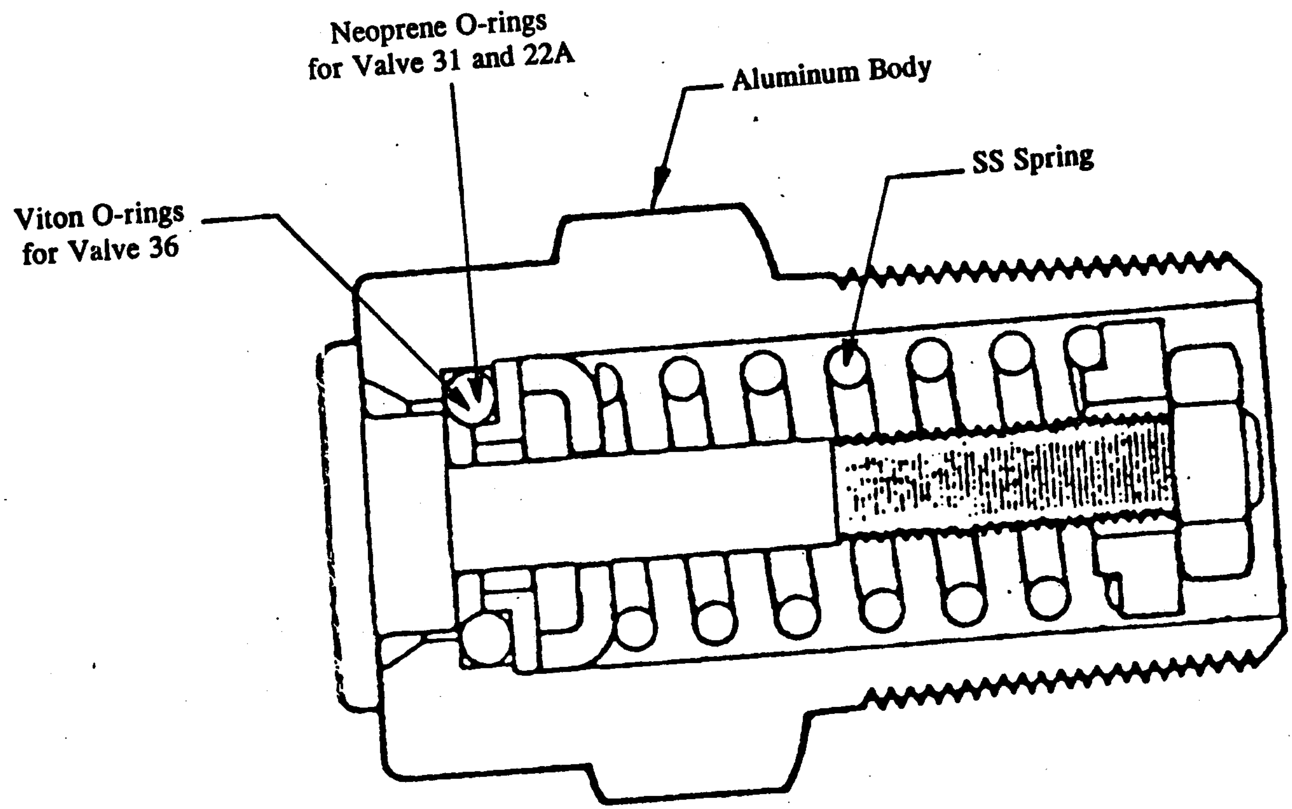

Figure 14
Relief Valves 22A, 31, and 36

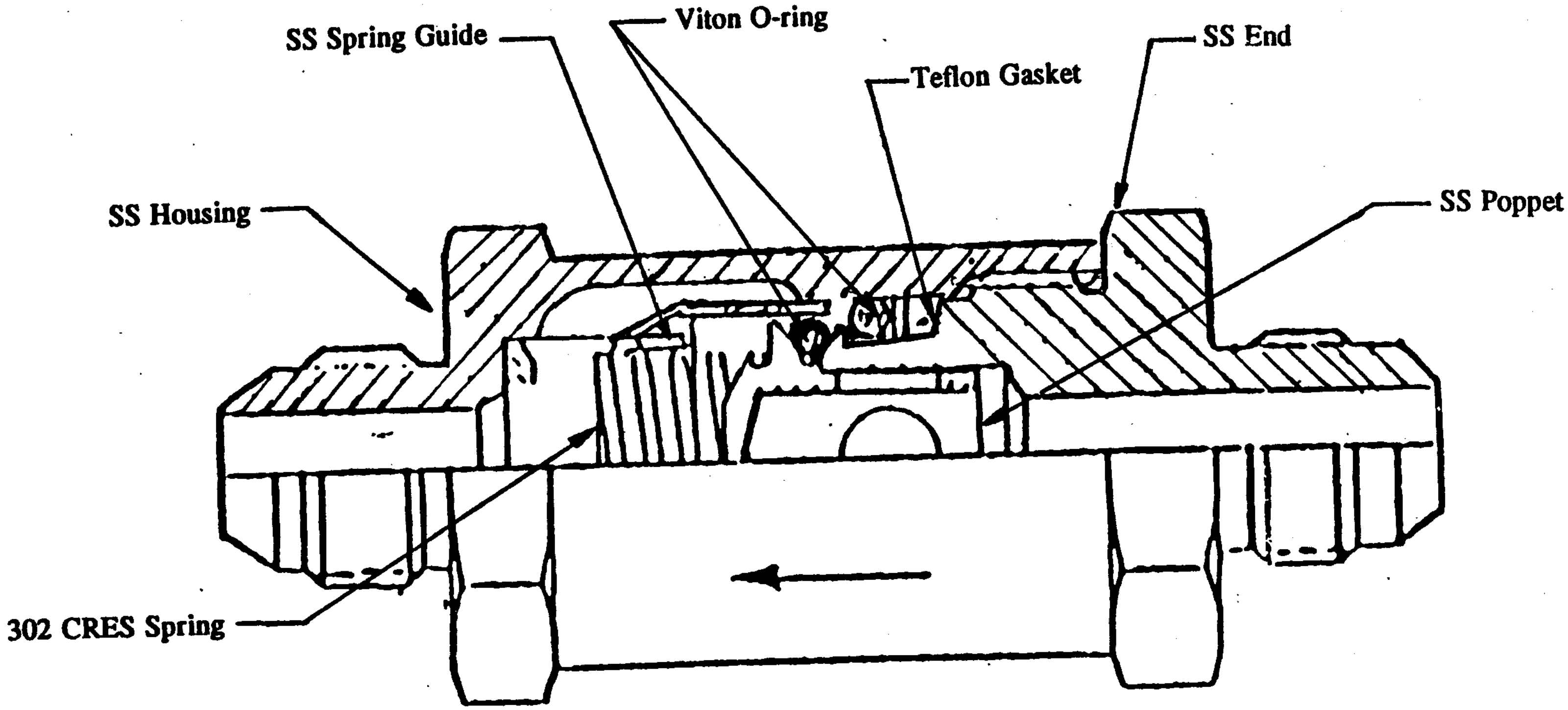

Figure 15
Check Valve 113

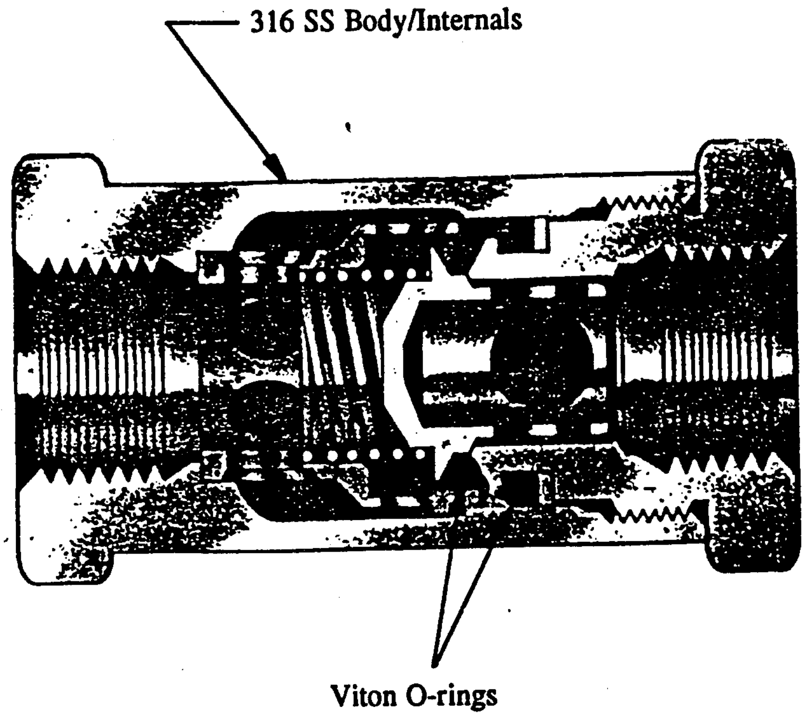

Figure 16
Check Valve 100

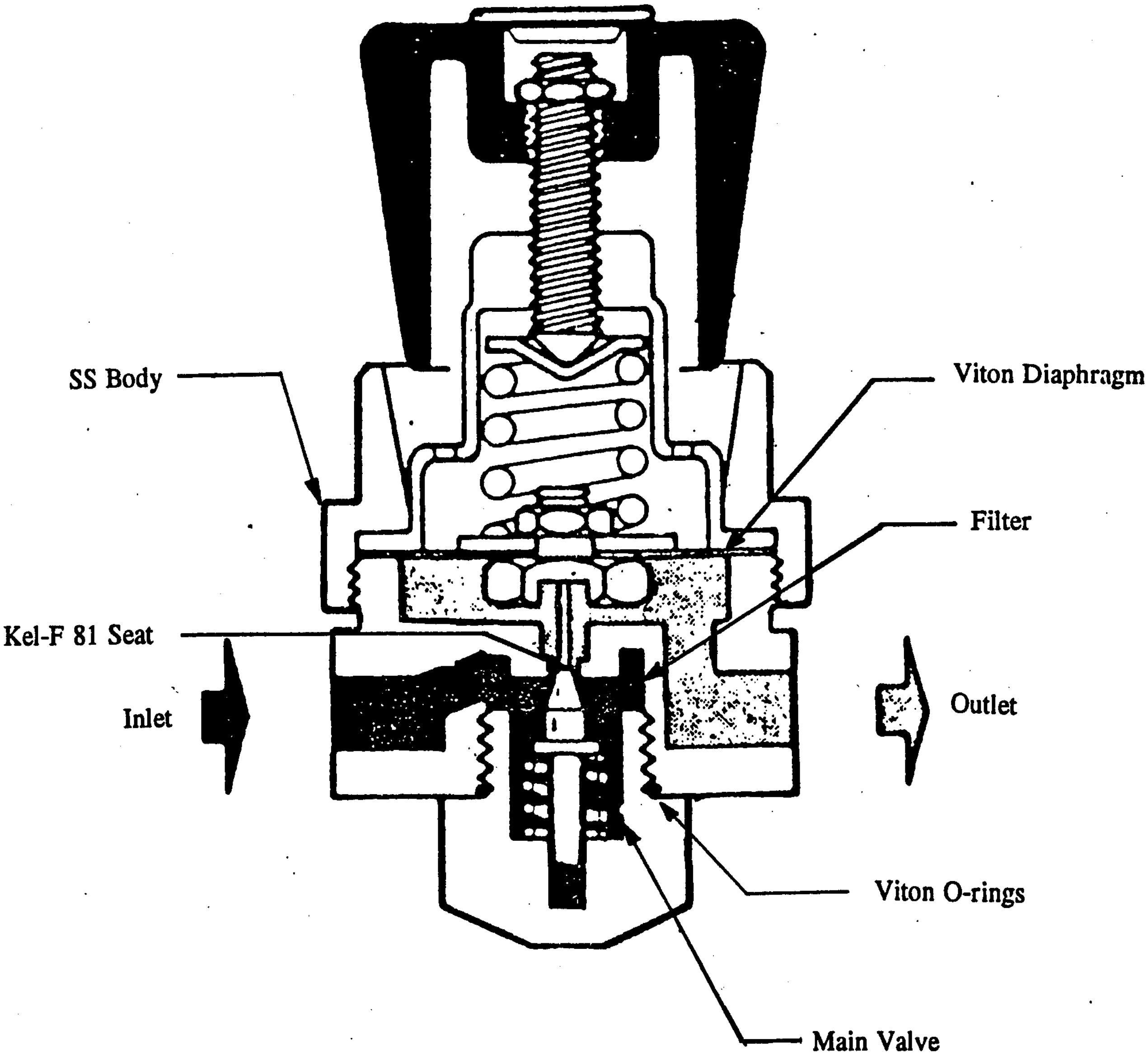

Figure 17
High-Pressure Regulators 38 and 115

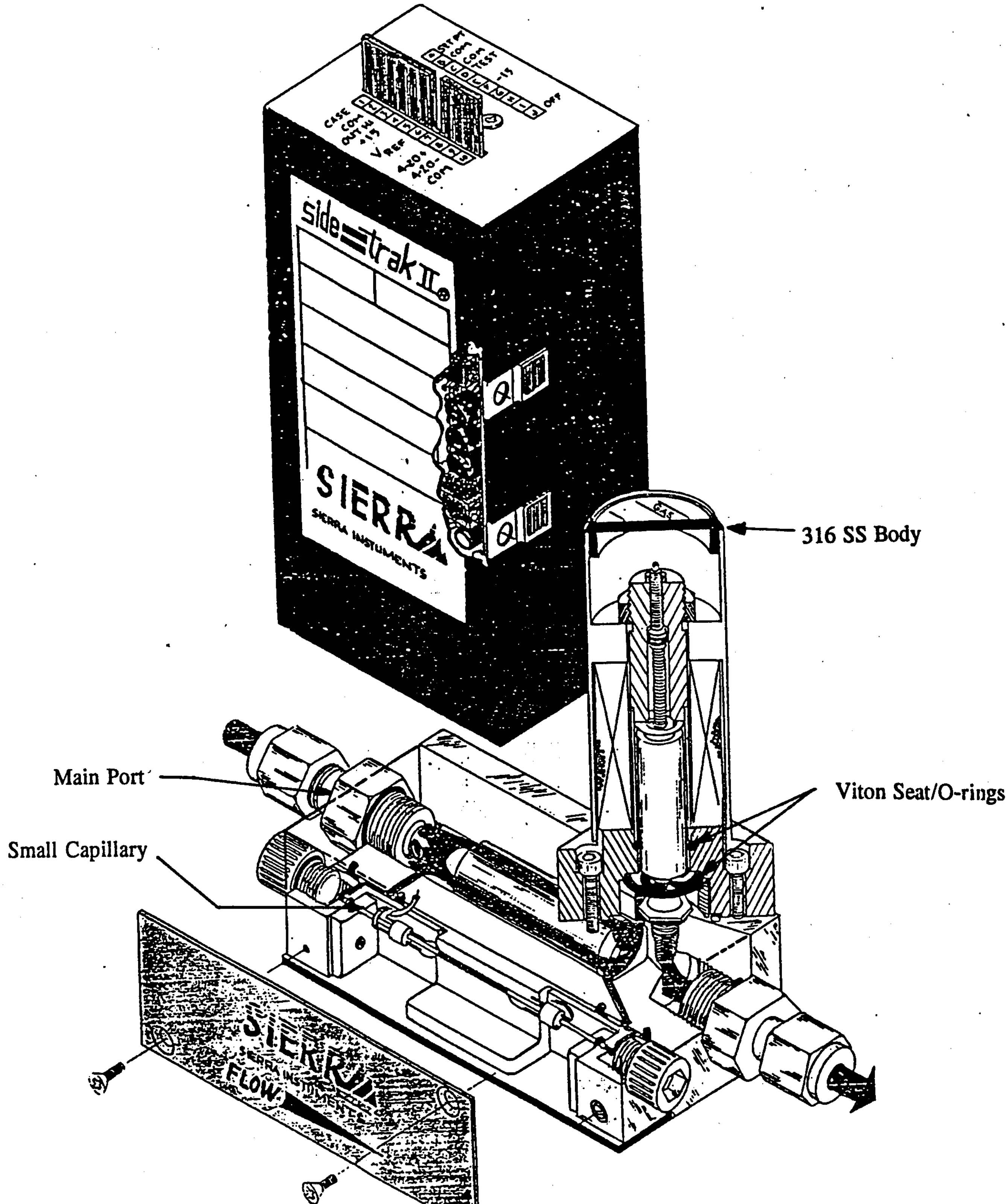

Figure 18
Mass Flow Controllers 44 and 44B

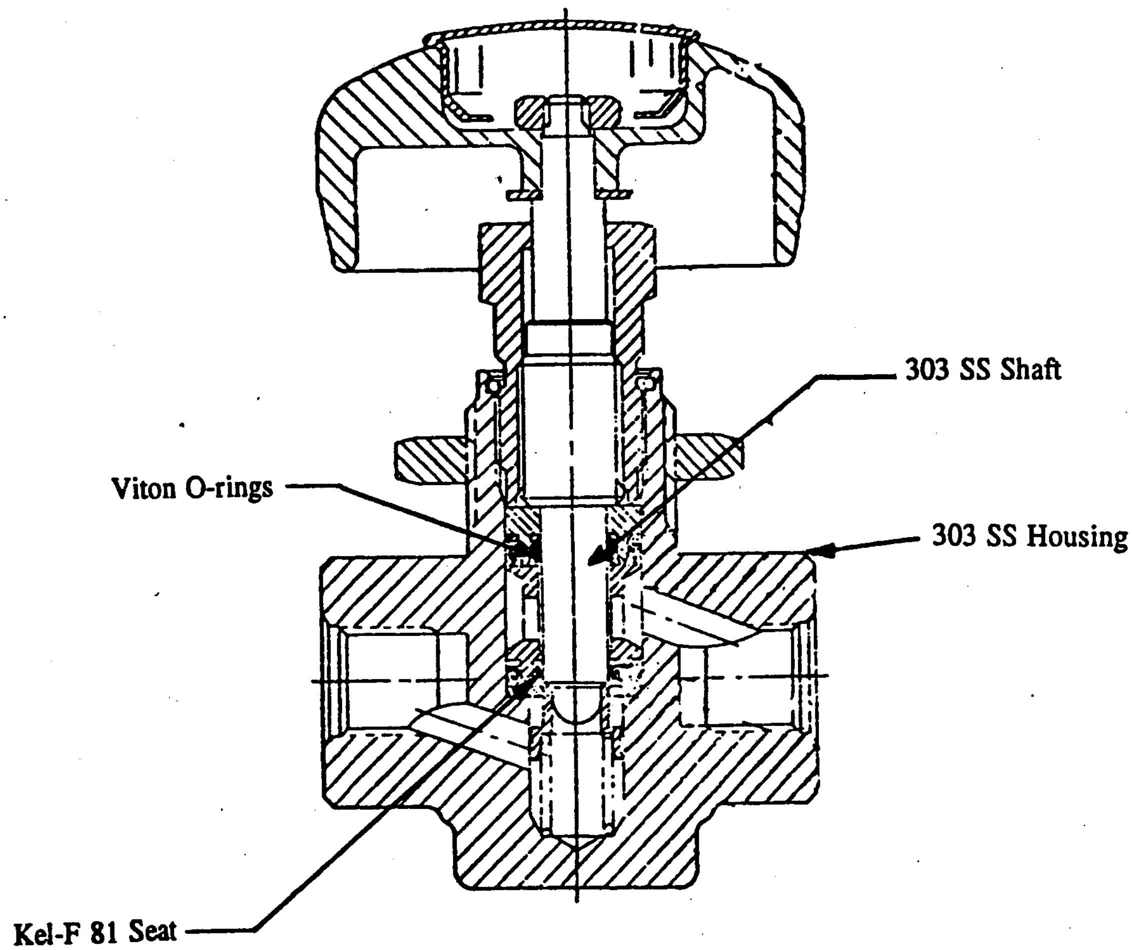

Figure 19
Manual Valves MV1 (29A), MV2 (29A), MV4 (117), and MV5 (52C)

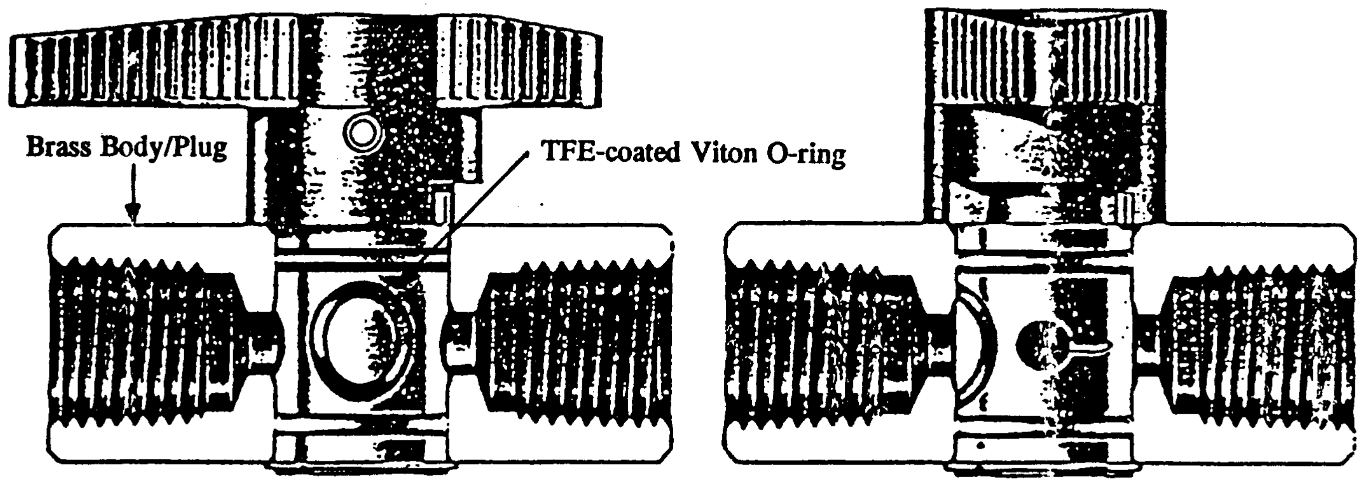

Figure 20
Manual (Plug) Valve MV3 (29)

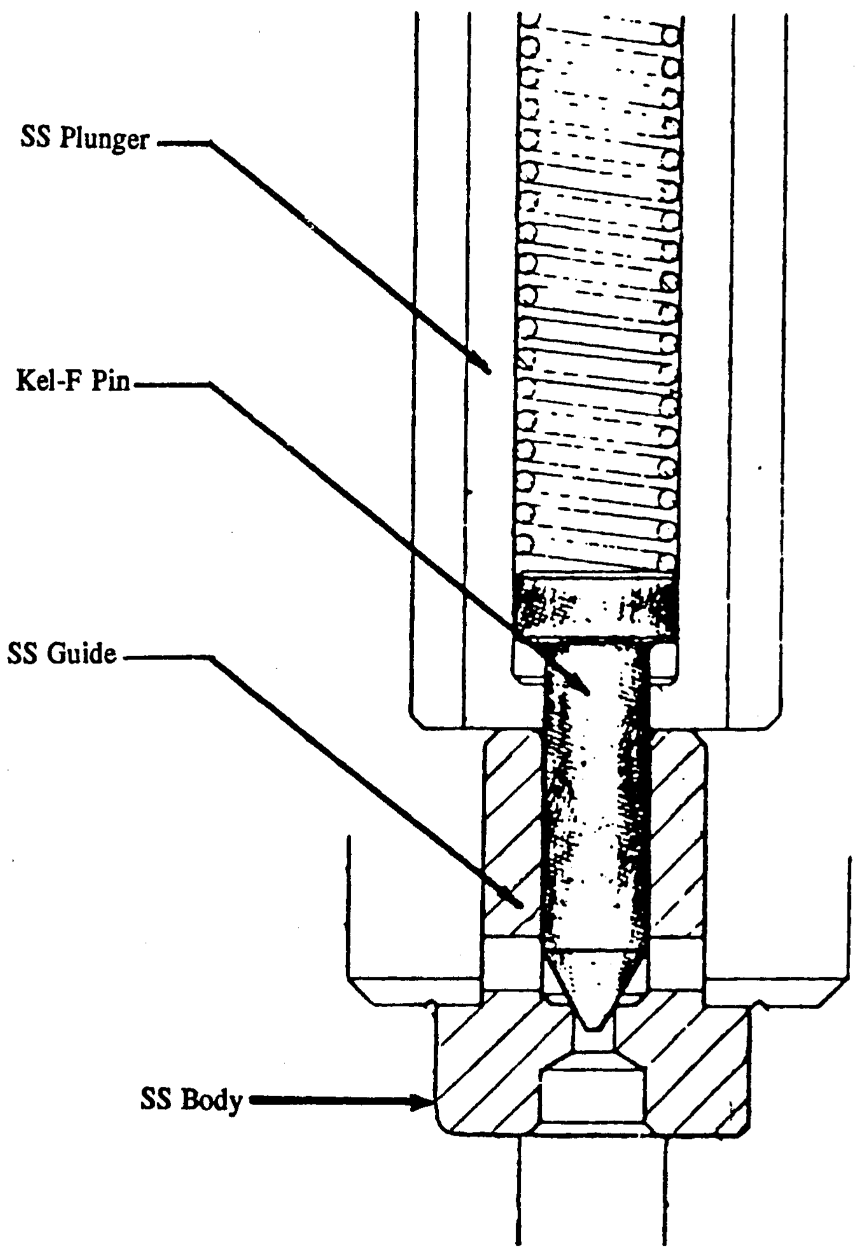

Figure 21
Solenoid Valves 115A and 133

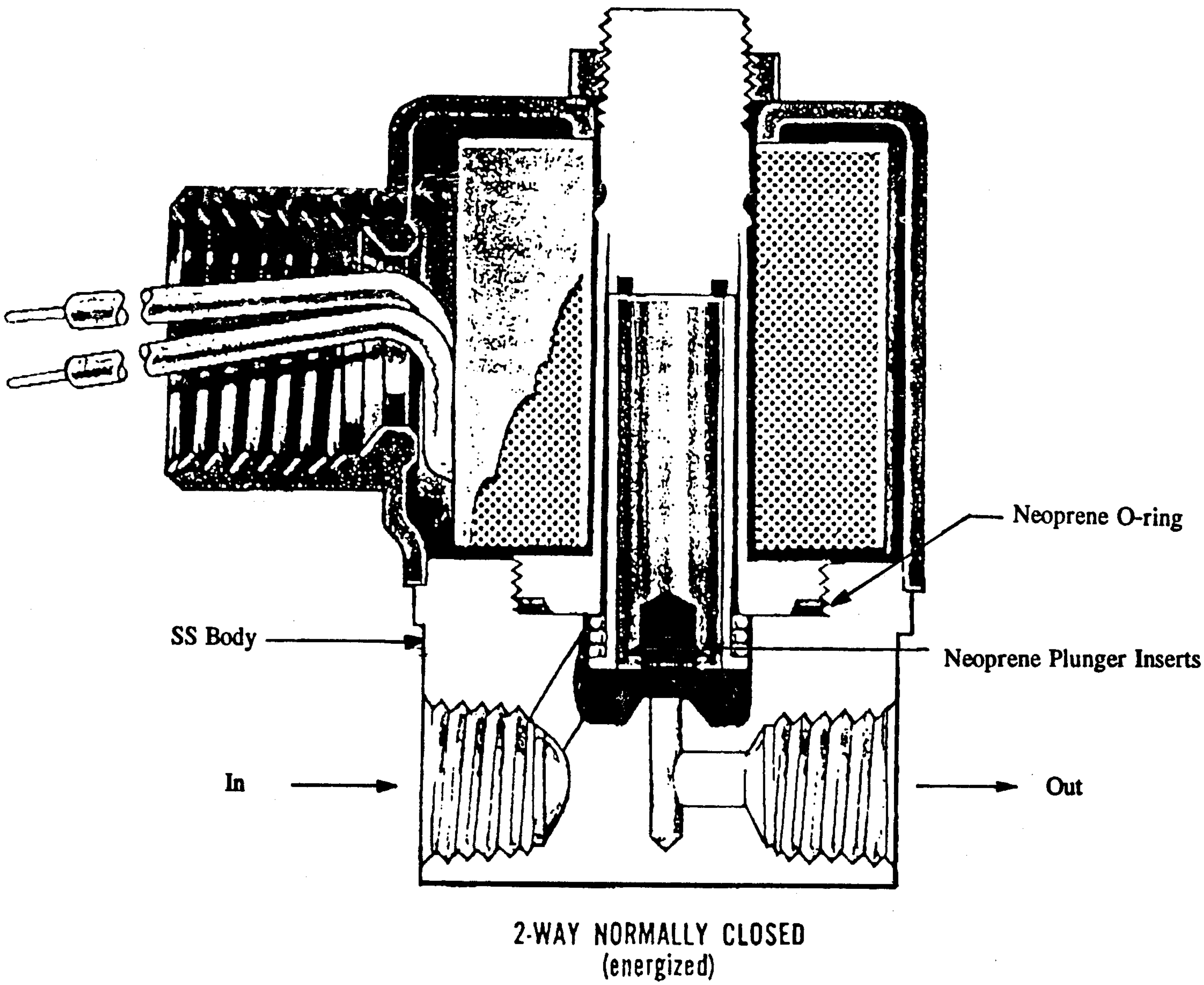

Figure 22
Solenoid Valves 33, 100A, and 136A

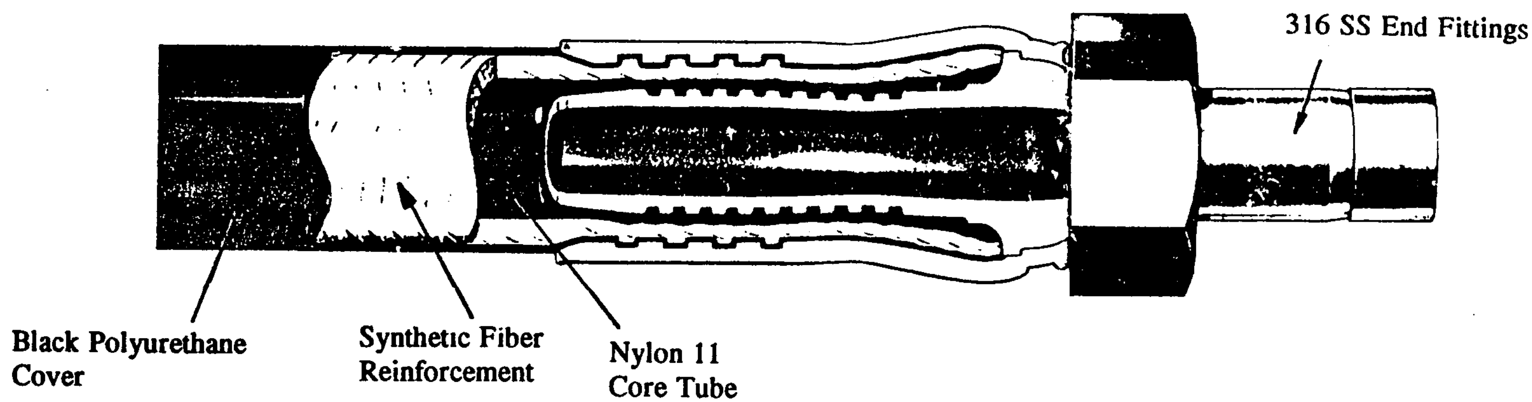

Figure 23
High/Low Pressure Flexhoses

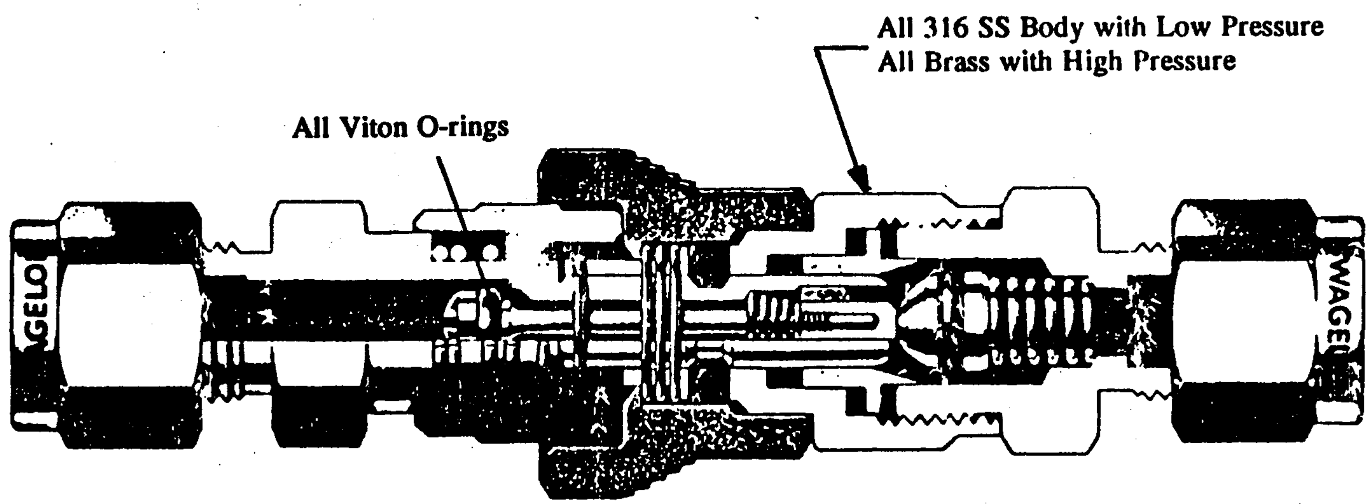

Figure 24
Quick Disconnect

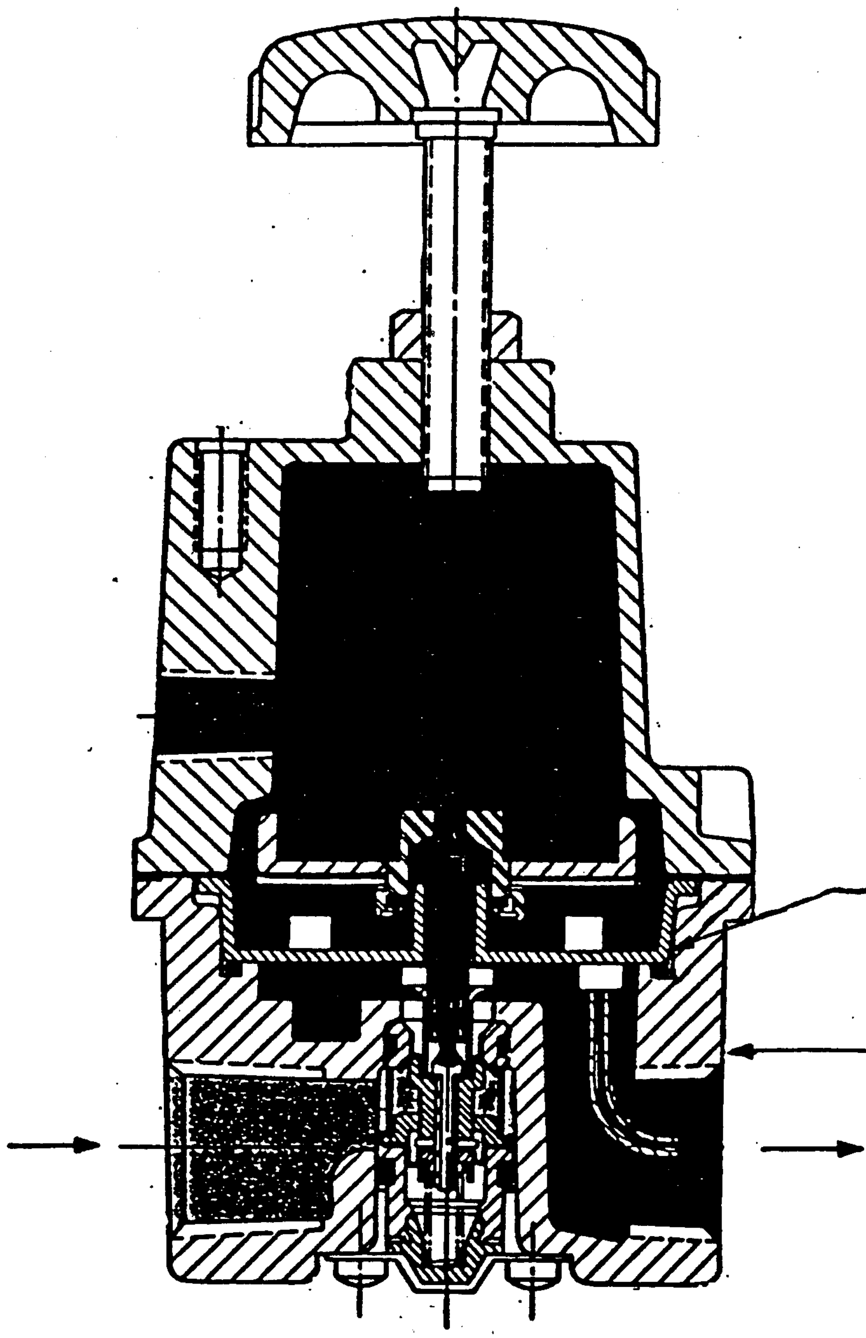

Figure 25
High Flow Regulator 52AA

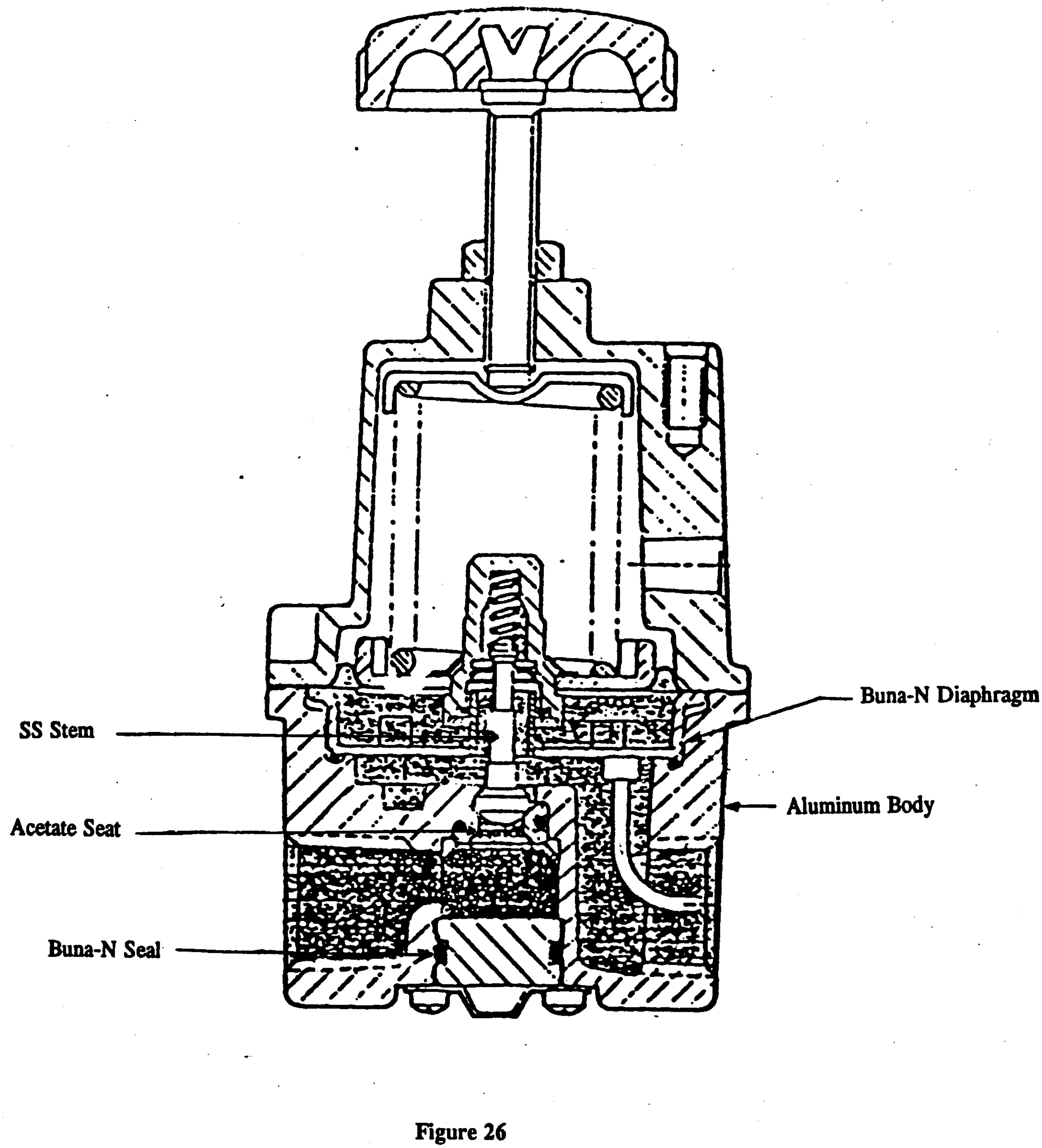

Figure 26
High Flow Regulator 35

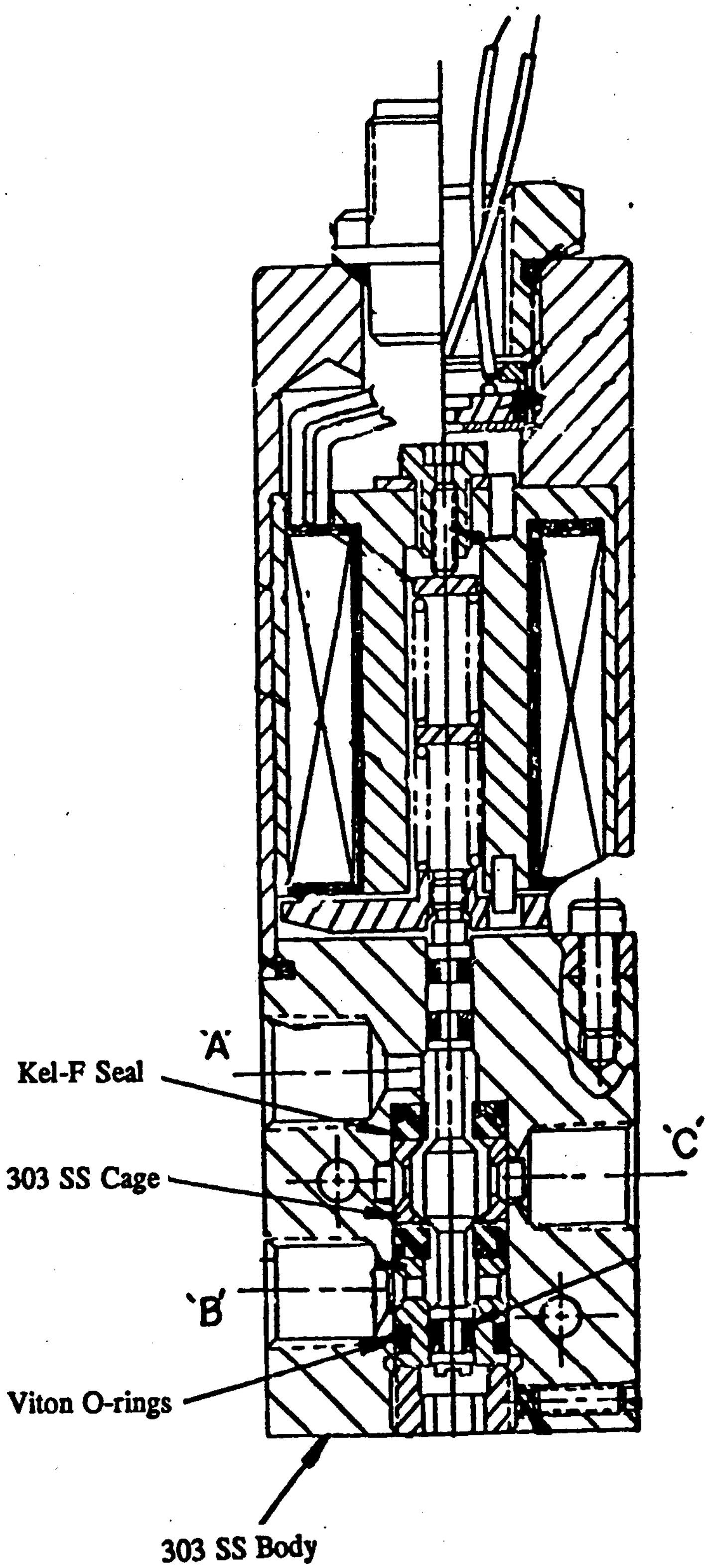

Figure 27
Back-up Oxygen Valve 37

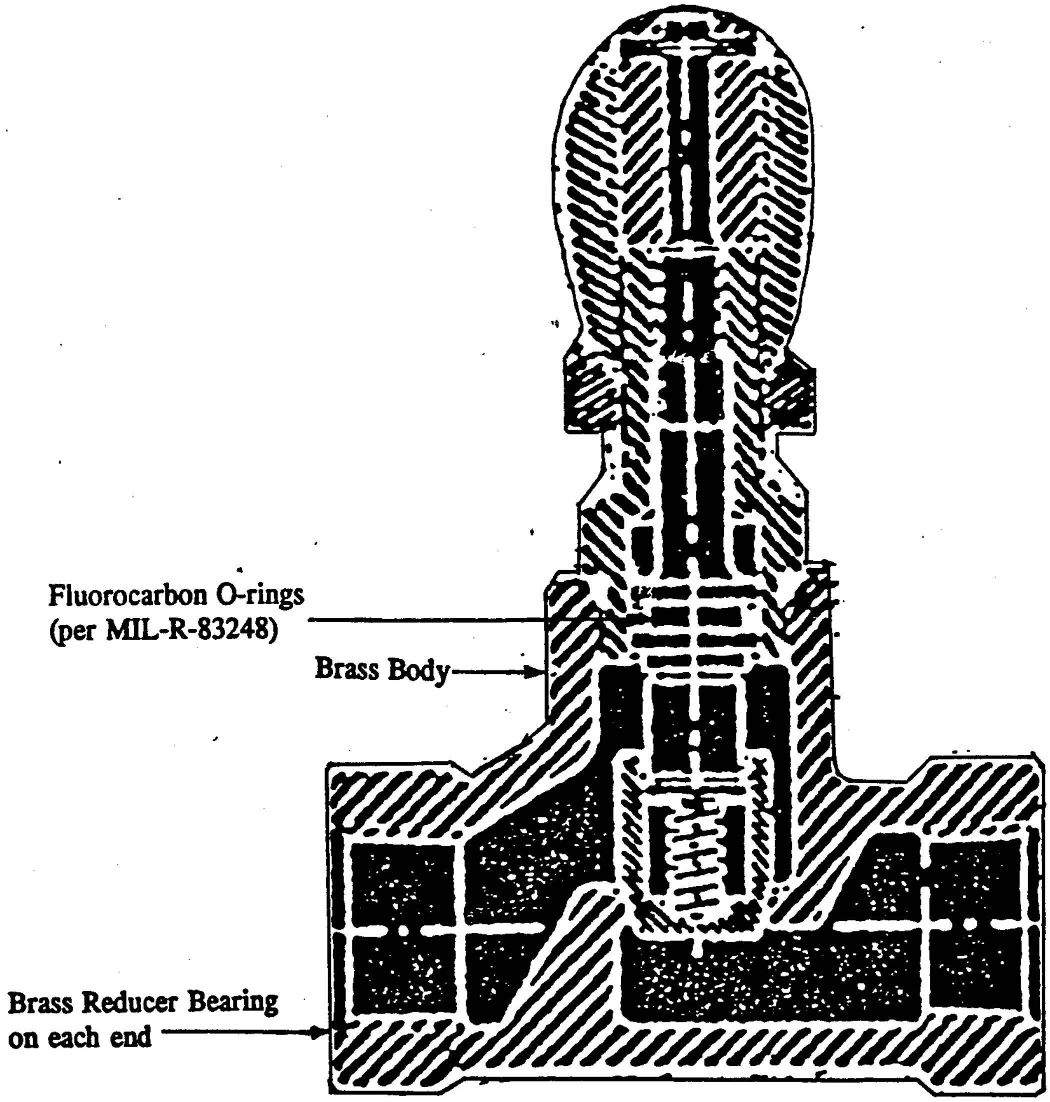

Figure 28
Constant Purge Valve 25

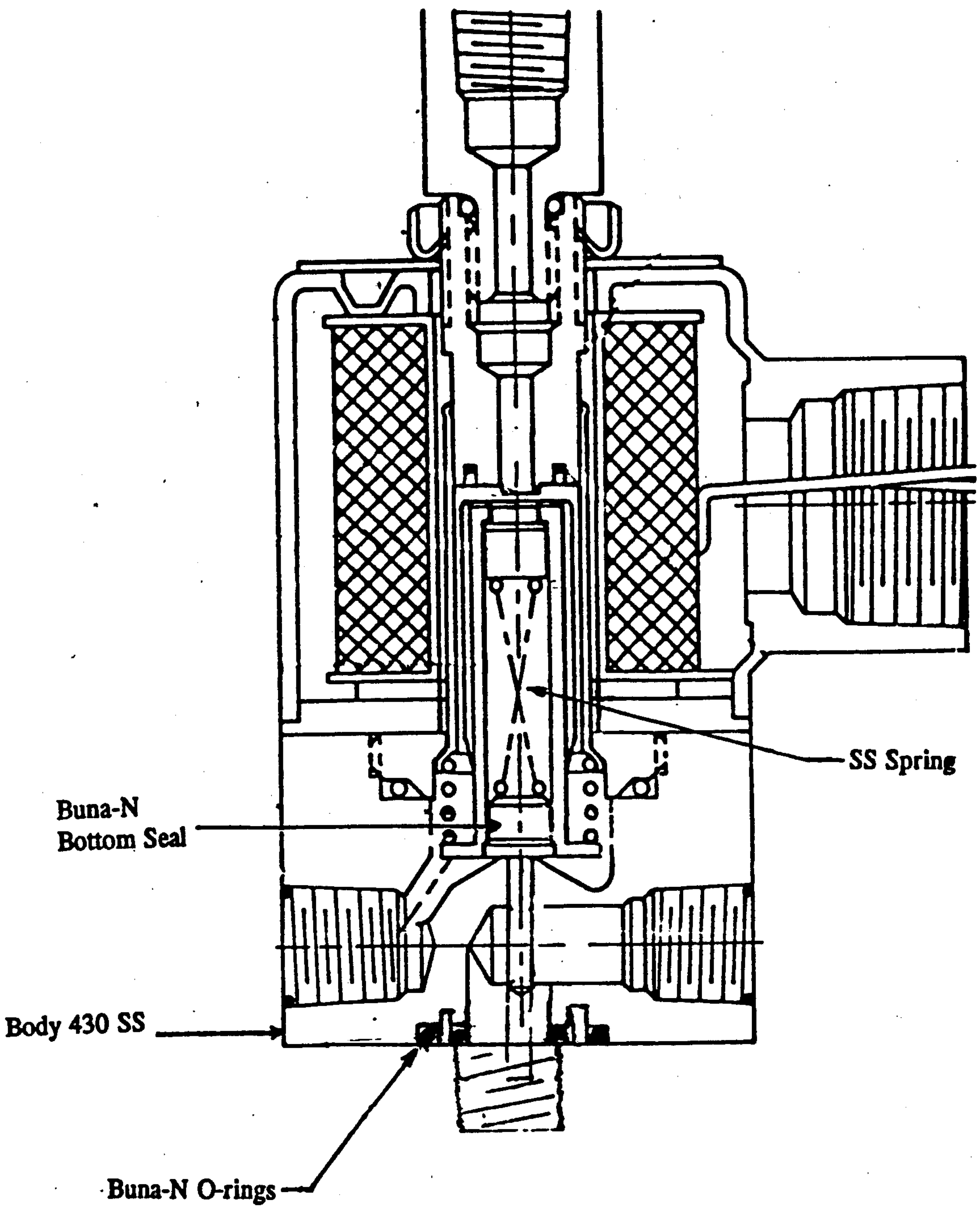

Figure 29
Purge Control Valve 24

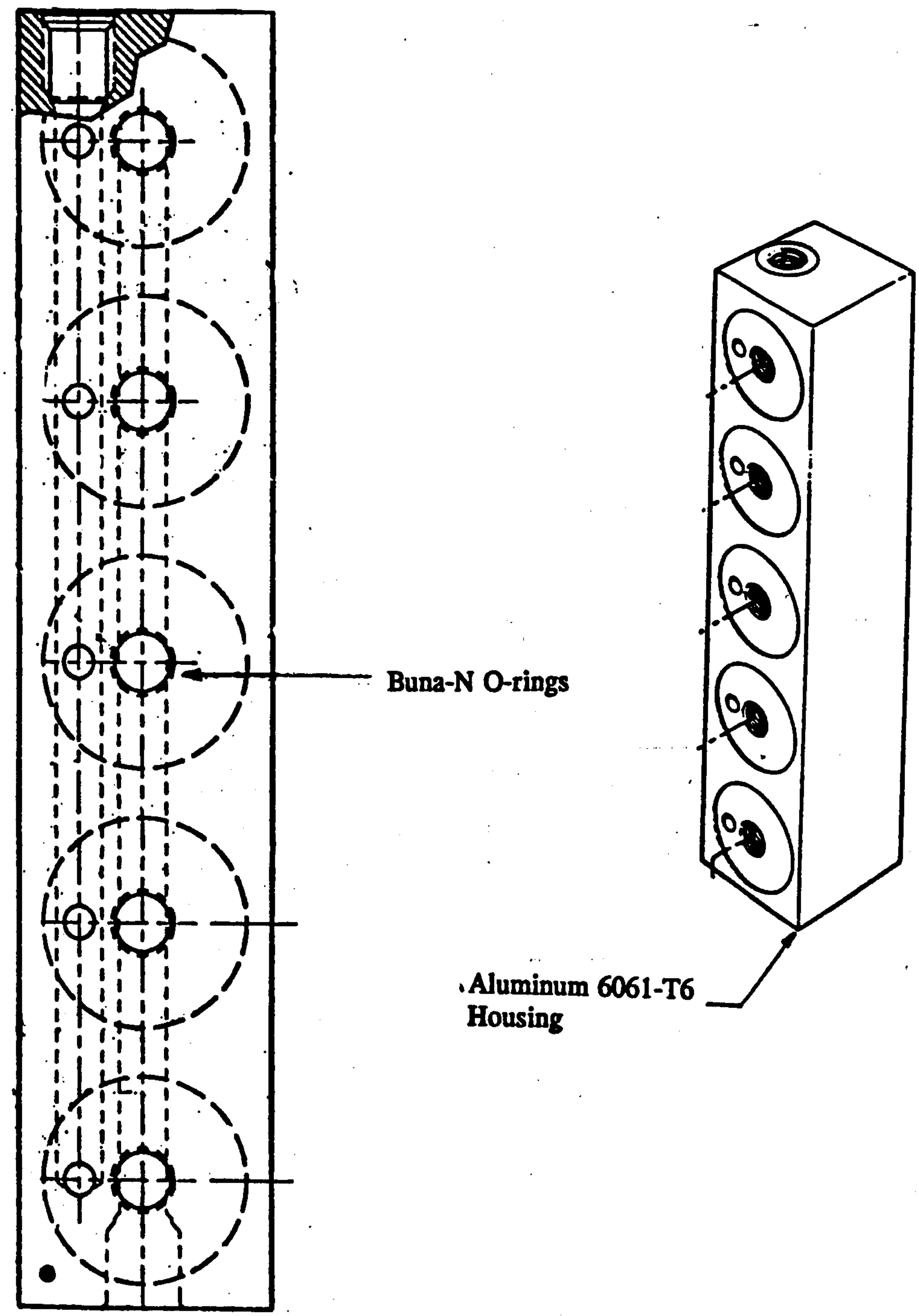

Figure 30
Purge Control Valve Manifold

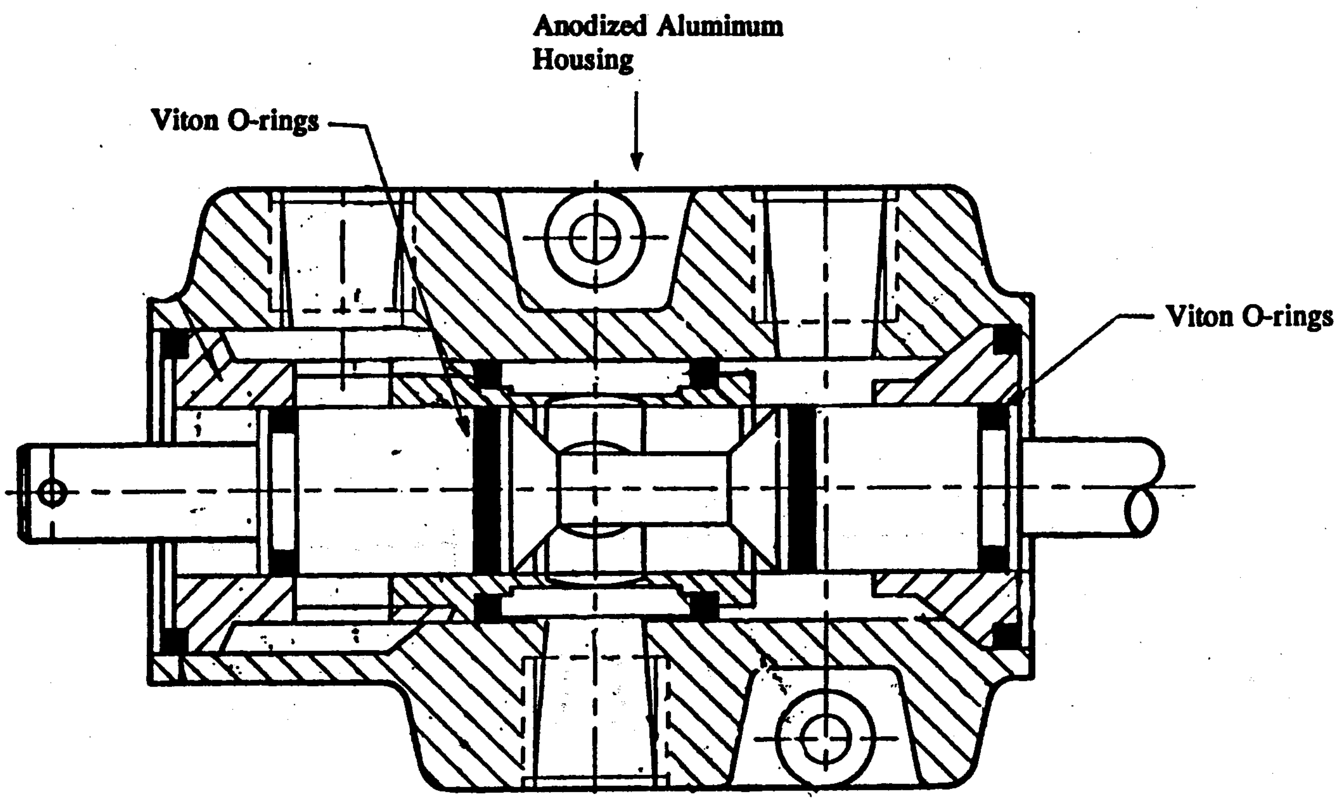

Figure 31
Equalization Valve 23

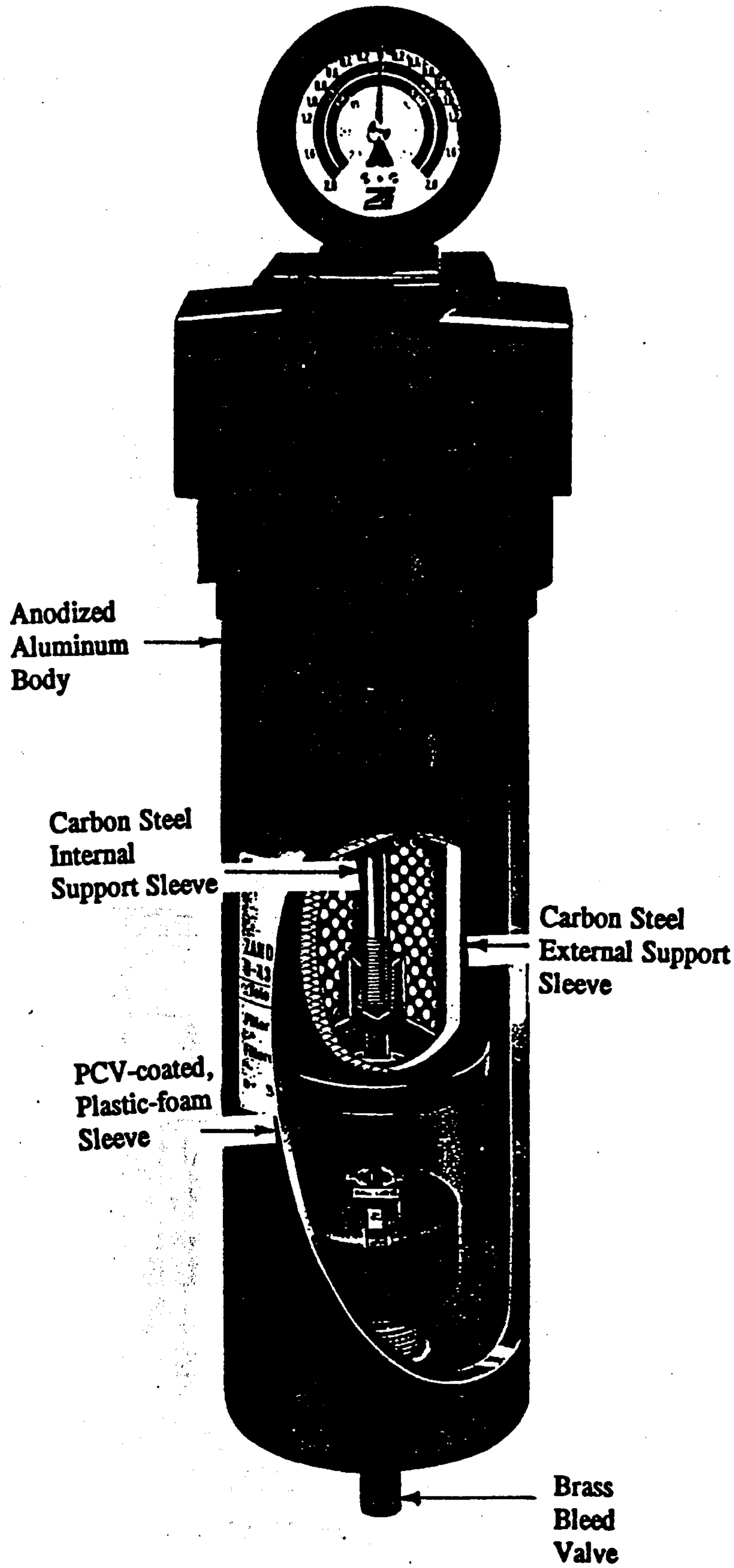

Figure 32
Product Filters 43 and 101

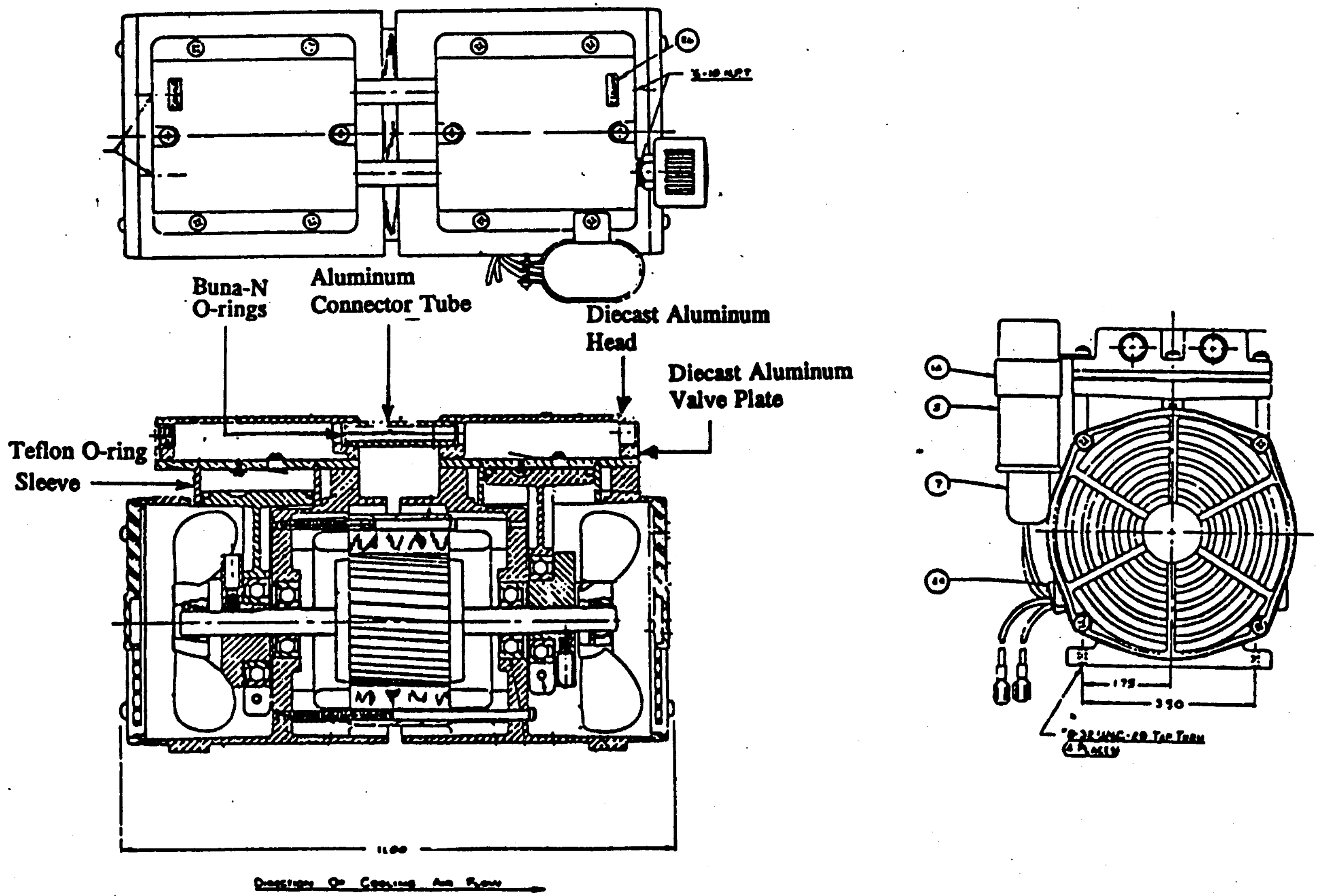

Figure 33
Vacuum Compressor 134

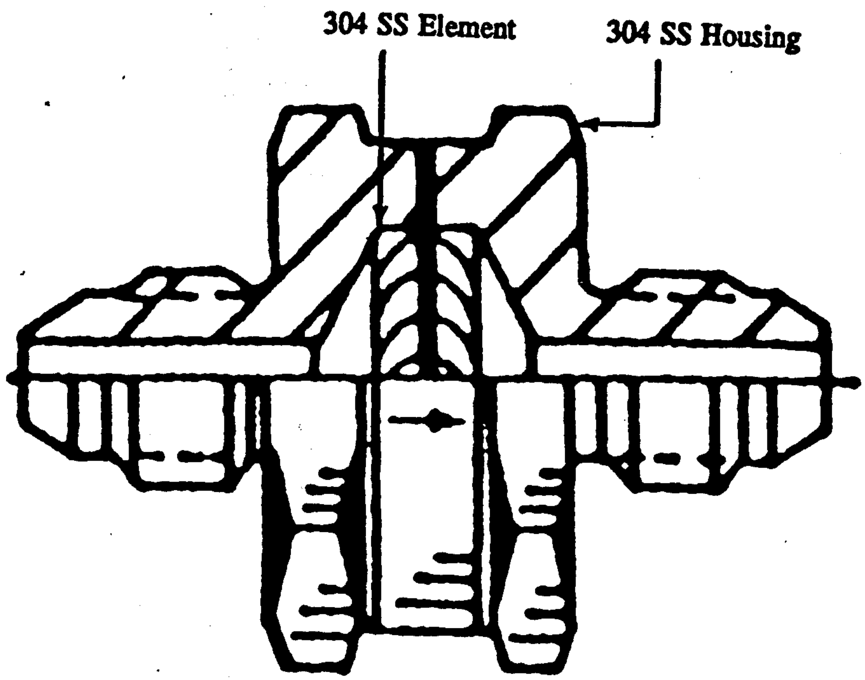

Figure 34
Oxygen Filter 132

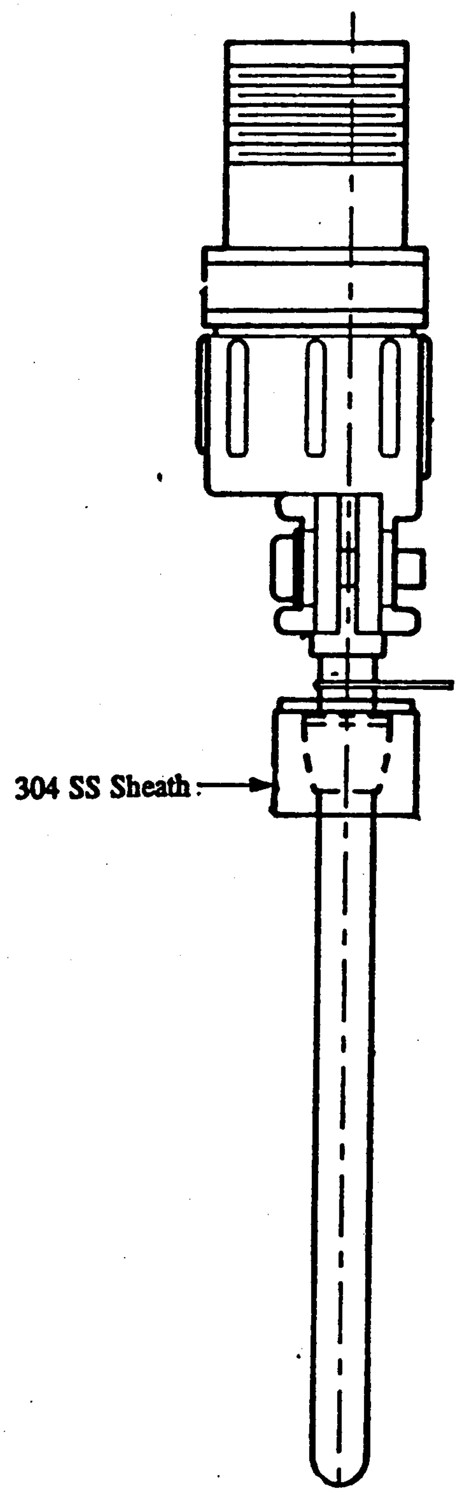

Figure 35
Temperature Indicators 112, 112B through 112F

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